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Enhancement of forward suppression begins in the ventral cochlear nucleus

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ABSTRACT

A neuron's response to a sound can be suppressed by the presentation of a preceding sound. It has been suggested that this suppression is a direct correlate of the psychophysical phenomenon of forward masking, however, forward suppression, as measured in the responses of the auditory nerve, was insufficient to account for behavioural performance. In contrast the neural suppression seen in the inferior colliculus and auditory cortex was much closer to psychophysical performance. In anaesthetised guinea-pigs, using a physiological two-interval forced-choice threshold tracking algorithm to estimate suppressed (masked) thresholds, we examine whether the enhancement of suppression can occur at an earlier stage of the auditory pathway, the ventral cochlear nucleus (VCN). We also compare these responses with the responses from the central nucleus of the inferior colliculus (ICc) using the same preparation. In both nuclei, onset-type neurons showed the greatest amounts of suppression (16.9–33.5 dB) and, in the VCN, these recovered with the fastest time constants (14.1–19.9 ms). Neurons with sustained discharge demonstrated reduced masking (8.9–12.1 dB) and recovery time constants of 27.2–55.6 ms. In the VCN the decrease in growth of suppression with increasing suppressor level was largest for chopper units and smallest for onset-type units. The threshold elevations recorded for most unit types are insufficient to account for the magnitude of forward masking as measured behaviourally, however, onset responders, in both the cochlear nucleus and inferior colliculus demonstrate a wide dynamic range of suppression, similar to that observed in human psychophysics.

Abbreviations: AC, auditory cortex; AN, auditory nerve; BF, best frequency; CF, characteristic frequency; Ch, chopper; CN, cochlear nucleus; CS, chopper-sustained; CT, chopper-transient; CV, coefficient of variation; DCN, dorsal cochlear nucleus; GoS, growth of suppression; IC, inferior colliculus; ICc, central nucleus of the inferior colliculus; ISI, inter-spike interval; ON, onset; OL, onset-L; OI, onset-I; OC, onset-chopper; OS, onset- sustained; P, pauser; PEST, parameter estimation by sequential testing; PL, primary-like; PN, primary-like with notch; PSTH, peri-stimulus time histogram; S, sustained; VCN, ventral cochlear nucleus

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1. Introduction

In the natural auditory environment, single tones rarely occur in isolation; most often auditory signals are comprised of complex patterns of spectral and temporal information, against background ambient noise. The perception of salient signals is highly context dependent and our knowledge of the mechanisms of how such processing occurs is incomplete. One important aspect for processing auditory signals is masking, defined as "the process by which the threshold for one sound is raised by the presence of another (masking) sound" (Moore, 2003). Physiological correlates of psychophysical forward masking have been measured using a two-tone paradigm. The first tone (*aka* the masker) is assumed to suppress the response to the second tone (*aka* the probe). At the level of the auditory nerve this phenomenon has been attributed to peripheral short-term adaptation in response to the masker tone (Kiang et al., 1965; Harris and Dallos, 1979). The early results of forward masking studies in the AN (e.g. Harris and Dallos, 1979) showed some similarities with psychophysical data (e.g. the periods of recovery from masking have similar time courses), however, differences in other parameters suggest that central auditory pathways contribute to the psychophysical phenomenon of forward masking.

Auditory nerve fibres terminate in the cochlear nucleus (CN), and several studies have shown a hierarchy of forward suppressed responses from the different unit types in the CN (Palombi et al., 1994; Backoff et al., 1997; Shore, 1998; Boettcher et al., 1990; Bleeck et al., 2006). The range of forward suppressed responses found in the CN is likely to be a reflection of the synaptic arrangements, cell-membrane properties, and the interneuronal circuitry associated with each cell type. The studies in the CN (and some in the AN) considered forward suppression as the difference in number of spikes evoked by a probe stimulus in the presence and absence of a preceding conditioner tone (Harris and Dallos, 1979; Boettcher et al., 1990; Palombi et al., 1994; Shore, 1995; Bleeck et al., 2006). This approach is problematic as it is unknown how spike count ratios relate to a potential change in neural threshold. To overcome this problem several studies have now measured the neurometric thresholds of single neurons at the level of the IC (Nelson et al., 2009) and auditory cortex (AC; Alves-Pinto et al., 2010; Scholes et al., 2011). It has been argued that the amount of suppression found in unit populations in the inferior colliculus (IC) of the marmoset (Nelson et al., 2009) and the auditory cortex of the guinea pig more closely resembles the magnitude and time course of forward masking as observed psychophysically in humans. In the IC a simple neural circuit was hypothesised to account for the data although it is still unknown whether the amount of suppression observed in the IC is created de novo or is simply a reflection of processing carried out at an earlier stage in the processing pathway. To test this we have quantified the magnitude of forward suppression in terms of dB threshold changes of suppressed probe tones, using identical stimulus paradigms, for neurons in the VCN, and in the IC. Units classified as onset-like, in both the VCN and IC, showed suppression that was greater in magnitude than that observed in a similar study in the auditory nerve.

2. Results

2.1. Single unit classification

Single unit recordings were obtained from 113 neurons in the left ventral CN of 27 animals. Neurons were classified according to their temporal discharge patterns in response to these BF tone bursts, using the schemes of Blackburn and Sachs (1989), Young et al. (1988) and Winter and Palmer (1995). This takes into account PSTH shape, distribution of inter-spike interval (ISI) and the coefficient of variation (CV) of discharge regularity (calculated by an average of the ratio of mean ISI, μ, and its standard deviation, σ, between 12–20 ms after onset). Examples of PSTHs for each class of neuron, recorded at 50 dB SL, are shown in Fig. 1. Primary-Like (PL) neurons had an exponential decline in ISI distribution. Primary-Like with Notch (PN) demonstrated a similar ISI pattern but had a pronounced reduction in PSTH spike rate subsequent to a precisely-timed first spike. Onset neurons had a precisely timed onset spike with a low standard deviation in first spike latency. Onset chopper (OC) neurons demonstrated a second peak in the PSTH response, especially at 50 dB above threshold, often with a low level sustained rate of activity. Onset-L (OL) neurons showed a similar response, but without the second peak. Onset-I (OI) neurons fired a single onset spike and showed no sustained rate even at high stimulus levels. Chopper units showed regular peaks in their PSTH; those with a CV value of less than or equal to 0.3 were classified as sustained choppers (CS), whereas those with a CV above 0.3 were defined as transient choppers (CT). Neurons with BFs below 0.5 kHz were routinely classified as low frequency (LF). Neurons that could not be classified by the above criteria were deemed unusual (UN) and are not discussed further. Using these criteria, the following distribution of neurons was recorded: OC ($n=12$), OI ($n=6$), OL ($n=5$), CS ($n=18$), CT ($n=39$), PL ($n=9$), PN ($n=12$), LF ($n=10$), UN ($n=2$).

Single unit recordings were also obtained from 77 neurons in the right ICc of 23 animals. Neurons were classified according to their temporal response patterns from PSTHs recorded in response to BF tones at 20 dB and 50 dB suprathreshold (using a scheme modified from Le Beau et al. (1996), Rees et al. (1997) and Syka et al. (2000)). Examples of PSTHs for each class of neuron, recorded at 50 dB SL, are shown in Fig. 2. The scheme used in the current study is described briefly. Chopper neurons demonstrated multiple peaks in their PSTH response with a CV value of 0.35 or lower. Onset-sustained neurons had an onset rate of >250 spikes/s and an onset-steady state discharge rate ratio >3 (with a CV>0.35). Pauser neurons demonstrated a reduction in spike rate (at least 7 ms in duration) relative to steady state rate of $>20\%$ within the first 15 ms of the onset of the response. Onset neurons demonstrated an onset rate: steady state rate ratio of >10 with a steady state rate of <30 spikes/s. Sustained neurons demonstrated a steady rate greater than 30 spikes/s, with no peculiar peak or trough in the response. Low frequency neurons demonstrated phase locking to the carrier frequency and had a BF of less than 500 Hz. Neurons that could not be classified by the above criteria were deemed 'Unusual' and are not discussed further. Using the above criteria, the