INTRODUCTION

The processing of auditory information carried by complex sounds has been explained by neural interactions based on divergent and convergent projections within the ascending auditory system, but without considering the contribution of the descending (corticofugal) auditory system (Suga 1997). However, recent studies have shown that the massive corticofugal system modulates and improves ongoing signal processing and reorganizes frequency map according to auditory experience in the central nucleus of bat inferior colliculus. However, whether all corticofugally affected collicular neurons are involved in both types of modulation has not been determined. In this study, we demonstrate that one group (51%) of collicular neurons participates only in corticofugal modulation of ongoing signal processing, while a second group (49%) of collicular neurons participates in both modulation of ongoing signal processing and in reorganization of the auditory system.

METHODS

One or two days before the recording session, a 1.8-cm nail was glued onto the exposed skull of each of nine pentobarbital sodium (Nembutal)-anesthetized (45–50 mg/kg body wt) bats (body wt 20–24 g). During recording, each bat was administered the neurolept-analgesia Innovar (0.08 mg/kg body wt of fentanyl, 4 mg/kg body wt of droperidol) and was strapped to an aluminum plate with transparent plastic sheeting inside a double-wall, sound-proof room (temperature 28–30°C). The bat’s head was immobilized by fixing the shank of the metal rod with a set screw (Suga and Schlegel 1972). Small holes were then bored in the skull above the primary auditory cortex (AC) and the IC.

Acoustic stimuli (4 ms with 0.5 ms rise-decay times at 2 pps) were generated with an oscillator (KH model 1200) and a homemade electronic switch. These stimuli were then amplified after passing through a decade attenuator (HP 350D) before they were fed to a small condenser loudspeaker (AKG model CK 50, 1.5 cm diam, 1.2 g) that was placed 23.5 cm away from the bat and at 40° contralateral to the recording site. The loudspeaker was calibrated with a Bruel & Kjær 1/8-in. (4135) microphone placed at the bat’s head. The output was expressed in dB SPL in reference to 20 μPa root mean square.

During experiments, custom-made, two tungsten-in-glass electrodes, described previously (Jen et al. 1998) (tip: <10 μm, inter-tip distance: 30–50 μm), were inserted into the AC at depths of 500–700 μm (the 5th layer of the AC) (Jen et al. 1997). When a single neuron was isolated, the frequency and intensity of the sound were systematically varied to determine the best excitatory frequency (BF 2 AC) at which the neuron had the lowest threshold to sound stimulus (i.e., the minimum threshold or MT 2 AC). At the MT 2 AC, the neuron responded to each of two consecutive presentations of BF 2 AC pulses. The neuron’s latency 2 AC to a BF 2 AC sound at 10 dB above the MT 2 AC was determined.

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ms) such that the neuron’s response was either decreased or increased at least 20%. The electrical current (5–50 μA, usually 5–25 μA) that produced a 30–50% change in response relative to the control response was then chosen for subsequent experiments.

To determine whether corticofugal modulation of the response of a collicular neuron had different time courses, the neuron’s response was monitored under two stimulation conditions. First, the responses of each corticofugally affected collicular neuron to ASIC alone and to ASIC + ESAC were monitored when the ESAC was delivered at 2 trains/s. The neuron’s response to ASIC was also monitored on cessation of ESAC and at 5-min intervals for 35 min thereafter. Second, an ESAC at 10 trains/s and a BFAC sound at 10 dB above the MTAC was delivered for 30 min (referred to as ASIC + ESAC stimulation conditions). The neuron’s response to ASIC was then monitored on cessation of ASIC and ESAC at 5-min intervals for 35 min thereafter. This ASIC + ESAC stimulation condition was comparable to the one used in previous studies that produced short-term corticofugal modulation (Gao and Suga 1998; Yan and Suga 1998).

Recorded action potentials were amplified with conventional techniques and sent to a computer (Gateway 2000, 486) for acquisition of peristimulus time histograms (binwidth: 500 μs, sampling period: 100 ms) of the neuron’s responses to 32 stimuli. The total number of impulses in each histogram was used to quantify the neuron’s response under each stimulation condition.

RESULTS

In this study, 30 corticofugally inhibited and 9 corticofugally facilitated collicular neurons were isolated. The effect of corticofugal modulation in 20 (51%, 16 corticofugally inhibited and 4 facilitated) collicular neurons vanished within 5–10 s following cessation of either ASIC or ASIC + ESAC. The neuron’s response to ASIC + ESAC produced a 30–50% change in response relative to the control response, and the neuron’s response after 30–50% change in response relative to the control response was then chosen for subsequent experiments.

For convenience, this type of corticofugal modulation is called brief corticofugal modulation. In contrast, the effect of corticofugal modulation in the remaining 19 (49%, 14 corticofugally inhibited and 5 facilitated) collicular neurons persisted up to 5–35 (average 20 ± 9.0) min following cessation of ASIC + ESAC. This type of corticofugal modulation is called short-term corticofugal modulation.

Figure 1 shows the discharge pattern, the number of impulses, MTIC and latencyIC of a representative corticofugally inhibited collicular neuron that displayed both brief and short-term corticofugal modulation. This neuron discharged a total of 81 or 82 impulses to ASIC (the control response). During ASIC + ESAC, the neuron’s number of impulses decreased from 81 (Fig. 1Aa) to 41 (Fig. 1Ab). The number of impulses increased to 76 following cessation of ASIC + ESAC and was between 76 and 80 when monitored up to 25 min thereafter (Fig. 1Ac). In contrast, the neuron’s number of impulses decreased from 82 to 39 (Fig. 1Aa, i–j) and slowly returned to within 5% of the control level over a period of 35 min following ASIC + ESAC (Fig. 1Aa, j–q). Figure 1, B–D, shows the time course of both brief and short-term corticofugal modulation on the neuron’s auditory responses. Variation in the number of impulses (in percent change), the MT and the latency during ASIC + ESAC (Fig. 1, B–D, filled triangles) returned to within 5% of the control level (Fig. 1, B–D, open triangles) on cessation of ASIC + ESAC and remained at the same level even when monitored for 25 min thereafter (Fig. 1B, B–D, open circles). However, variations in the neuron’s responses only gradually returned to within 5% of the control level over a
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FIG. 2. Brief and short-term corticofugal facilitation on auditory responses of a collicular neuron. A: the neuron’s PST histograms obtained with an ASIC before (A, a and i), during (Ab) and after (A, c–h and j–q) the ESAC. This neuron discharged 45 (Aa) or 46 (Ai) impulses to ASIC (shown in short horizontal bar). During ASIC + ESAC, this neuron discharged a total of 64 (Ab) impulses. On cessation of ASIC + ESAC, the neuron’s number of impulses in response to AC decreased to 48 (Ab), which varied between 44 and 48 when monitored over a period of 25 min (A, d–h). However, on cessation of ASIC + ESAC, the number of impulses was increased to 70, which gradually returned to within 2% of the control value (Ai) over a period of 25 min (Ao). B–D: time course for variation in the number of impulses (B), MT (C), and latency (D) during brief (open circles, Ba, Ca, and Do) and short-term (filled circles, Bb, Cb, and Db) corticofugal facilitation. The neuron’s number of impulses, MT, and latency determined under ASIC and ASAC + ESAC stimulation conditions are shown in open and filled triangles. The BF (kHz), MT (dB SPL), and latency (ms) of the IC and AC neurons were 38.1, 51, 9 (IC); 36.4, 56, 15 (AC; see Fig. 1 for legends).

Figure 2 shows both brief and short-term corticofugal modulation in the auditory response of a representative corticofugally facilitated collicular neuron. This neuron discharged a total of 45 or 46 impulses to ASIC. During ASIC + ESAC, the neuron’s number of impulses increased from 45 (Fig. 2Aa) to 64 (Fig. 2Ab). The number of impulses decreased to 48 on cessation of ASIC + ESAC (Fig. 2Ac) and was between 44 and 48 within the subsequent 25 min (Fig. 2Ad–h). In contrast, the number of impulses increased from 46 to 70 (Fig. 2Aj) and did not return to within 2% of the control level until 25 min after ASAC + ESAC (Fig. 2Ao). Variation in the number of impulses, the MT, and the latency during ASIC + ESAC (Fig. 2, B–D; filled vs. open triangles) returned to within 5% of the control level after ASIC + ESAC and remained at the same level when monitored for 25 min thereafter (Fig. 2, B–D, open circles). However, the neuron’s varied responses only gradually returned to within 5% of the control level over a period of 25 min after ASAC + ESAC (Fig. 2, B–D, filled circles).

Figure 3 shows responses of corticofugally inhibited (Fig. 3, A1–A3) and corticofugally facilitated (Fig. 3, B1–B3) collicular neurons that were involved only in brief corticofugal modulation. Their responses returned to within 5% of the control level (Fig. 3, filled vs. open triangles) after both ASIC + ESAC and ASAC + ESAC. These two neurons had similar recovery time course for both stimulation conditions (Fig. 3, open vs. filled circles).

Previous studies (Gao and Suga 1998; Yan and Suga 1998) reported that ASAC + ESAC produced an asymmetrical BFIC shift toward BFAC when BFIC was within 10 kHz above the BFAC and the maximal BFIC shift occurred when the BFAC-IC difference between cortical and cortical neurons was ~5 kHz. Among 19 neurons that were involved in both brief and short-term corticofugal modulation, the BFICs of four corticofugally inhibited and three corticofugally facilitated collicular neurons were above the BFAC by 0.23–2.91 kHz. ASAC + ESAC produced a BFIC shift toward to BFAC in two neurons with BFIC above the corresponding BFAC by 1.91 and 2.91 kHz. However, the BFIC shifts due to ASAC + ESAC in five other neurons were too small to determine confidently.

We examined the BFAC-IC difference in relation to brief and short-term corticofugal modulation. As shown in Table 1, BFAC-IC difference was significantly larger in collicular neurons that were only involved in brief corticofugal modulation (e.g., Fig. 3) than in collicular neurons that were involved in both types of corticofugal modulation (e.g., Figs. 1 and 2; t-test, P < 0.001). Although not significant, BFAC-IC difference within each group of collicular neurons was smaller for corticofugal facilitation than for corticofugal inhibition (t-test, P > 0.05).

DISCUSSION

Our finding of brief corticofugal modulation confirms that the corticofugal system can actively modulate collicular responses through inhibition (Fig. 1A, b–h, and B–D, open circles) and facilitation (Fig. 2A, b–h, and B–D, open circles) to improve ongoing signal processing. We found that short-term modulation of collicular responses (e.g., Figs. 1 and 2, A1–A3, B1–B3, filled circles) persisted for 5–35 (average...
20 ± 9.0) min after ASAC + ESAC. Variation in the number of impulses, the MT, and the latency during this time period suggests a plastic change in collicular auditory sensitivity. This finding supports earlier studies (Gao and Suga 1998; Yan and Suga 1998) that the corticofugal system contributes to neuroplasticity in the sensory system.

We have shown that one group of collicular neurons participated in both brief and short-term modulation (Figs. 1 and 2) and the other group participated only in brief corticofugal modulation of collicular signal processing (Fig. 3). The BFAC-IC difference in these two groups of collicular neurons was significantly different (Table 1). Future work is needed to determine whether these two groups of collicular neurons have different neural pathways for corticofugal modulation.

**TABLE 1.** The range and average difference in best frequency between cortical and collicular neurons based on the type and time course of corticofugal modulation

<table>
<thead>
<tr>
<th>Type</th>
<th>BFAC-IC Difference, kHz</th>
<th>Brief</th>
<th>Brief and short</th>
<th>t-Test, P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inhibition</td>
<td>8.3 ± 4.7 (16)</td>
<td>2.1 ± 1.9 (14)</td>
<td>&lt;0.0001*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[1.1–15.9]</td>
<td>[0.1–5.3]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facilitation</td>
<td>4.0 ± 1.4 (4)</td>
<td>1.6 ± 1.0 (5)</td>
<td>&lt;0.001*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[2.5–5.7]</td>
<td>[0.1–2.9]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t-Test, P</td>
<td>0.045</td>
<td>0.26</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SD; numbers in parentheses indicate number of neurons, and numbers in brackets are ranges. * Significant difference 1-tailed t-test, P < 0.001.

As described earlier, many recent studies (He 1997; Jen and Zhang 1999; Jen et al. 1998; Suga et al. 1997; Sun et al. 1989, 1996; Yan and Suga 1996, 1998; Zhang and Suga 1997; Zhang et al. 1997) have shown that the effect of corticofugal modulation can either be very brief or last for more than 3 h on cessation of ESAC. Furthermore, corticofugal modulation of sensory maps due to classical conditioning may last for periods ranging from 3 h to 8 wk (Weinberger et al. 1993). In this study, we used brief and short-term modulation to respectively describe a corticofugal modulation that vanished within 5–10 s or persisted up to 5–35 min following cessation of ESAC (Figs. 1 and 2, Aa–Ah, and Ba, Ca, and Da; and Fig. 3). To avoid confusion when comparing studies of auditory corticofugal modulation in the future, we propose that short-term modulation includes corticofugal modulation that lasts up to 3 h. We also propose that long-term modulation be used to describe corticofugal modulation associated with classical conditioning experiments, which lasts for more than 3 h.

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**REFERENCES**


