Correlation between neural discharges in cat primary auditory cortex and tone-detection behaviors

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\begin{abstract}
Understanding the physiological role of the auditory cortex (AC) in acoustic perception is an essential issue in auditory neuroscience. By comparing sound discrimination behaviors in animals before and after AC lesion, many studies have demonstrated that AC is necessary for the perceptual process of human vowels and animal vocalizations, but is not necessary to discriminate simple acoustic parameters such as sound onset, intensity and duration. Because a lesion study cannot fully reveal the function of AC under normal conditions, in this study, we combined electrophysiological recording and psychophysical experiments on the same animal to investigate whether AC is involved in a simple auditory task. We recorded the neural activities of the primary auditory cortex (A1) using implanted electrodes, while freely-moving cats performed a tone-detection task in which they were required to lick a metal tube to obtain a food reward after hearing a tone pip. The performance of the cats' behavioral response increased with the increase of tone intensity, and the neural activities of A1 covaried with the behavioral performance. Also, whether the tone-detection behavior was interfered by a wideband noise was dependent on whether the tone-evoked neural response was masked by the noise-evoked response. Our results did not support that A1 neurons directly associate with the cat's behavioral decision; instead, they may mainly generate a neural representation of stimulus amplitude for further processing to determine whether a tone occurred or not.

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\end{abstract}

1. Introduction

Although the involvement of the auditory cortex (AC) in acoustic perception seems widely accepted, it is less clear how the specific parts of this cortex contribute to different kinds of perception. To investigate this issue, a well-used approach is to inactivate or lesion the AC of animals and observe whether the capability of sound detection or discrimination is impaired. Such experiments have found that bilateral AC lesions resulted in significant elevations in the threshold for detecting the presence of gaps and sinusoidal amplitude modulation in noise sounds [1–3]. Also, the animals after bilateral ablations of AC were impaired in the discrimination of complex sounds, such as frequency patterns [4], frequency-modulated sounds [5,6], vowel-like stimuli [7], consonant–vowel–consonant sounds [8] and animal vocalizations [9–11]. These reported deficits had recovered little even after over a month.

On the other hand, AC is not necessary to discriminate some simple acoustic cues, such as the onset of a sound [12], changes in sound intensity [13–15], changes in frequency [16] and the duration of a tone [17]. These discriminations can be learned by animals with bilateral AC lesions. The fact that the discrimination of simple sounds can be relearned after AC lesions whereas the discriminations of complex sounds cannot be relearned may suggest that the auditory cortex is a crucial structure only for the processing of complex sounds. Since lesion studies cannot directly reveal the function of AC under normal conditions, AC may be involved in the perception of simple sounds, while its function is compensated for after reorganization of the central auditory system. This possibility has been indicated by the finding that a rat’s ability to detect tones was impaired soon after applying muscimol to reversibly inactivate the primary auditory cortex (A1) [18].

To well understand the role of AC in basic auditory perception, we also need to observe the activities of AC while the subjects are
performing auditory tasks. Human electroencephalography (EEG) and magnetoencephalography (MEG) experiments have revealed the modulation of AC activity depending on the subjects’ perceptual reports in the auditory signal detection task, that is, detected signals evoking AC responses were larger than undetected signals [19,20]. These findings in noninvasive human experiments have not been demonstrated by the electrophysiological recording of neural spike activities. This is because, in most previous electrophysiological studies, the subjects were not evaluating the stimuli and reacting accordingly, but rather perceived them passively or even while deeply anesthetized [21–28], and it is difficult to directly explain the perception phenomenon using such results. To address this question, we trained cats to detect pure tones from silent and noise backgrounds. While the cats participated in this task, we recorded the neural spike activities from chronic implanted electrodes in A1 of the cats. By comparing the neural activity with the cats’ behavioral performance on a trial-by-trial basis, we examined the functional roles of A1 in the tone-detection task: providing a neural representation of stimulus amplitude and/or associated with decision making?

2. Methods

All animal works were carried out in strict accordance with the recommendations in the Guide for the Care and Use of Laboratory Animals of the National Institutes of Health. The protocol was approved by the Committee on the Ethics of Animal Experiments of the University of Yamanashi (No. 19–15). All surgery was performed under sodium pentobarbital anesthesia, and all efforts were made to minimize suffering.

2.1. Apparatus

All training and testing sessions occurred in a custom-built behavioral cage that was acoustically transparent and placed in an electrically shielded, sound-attenuated chamber. Custom-built software in MATLAB (Mathworks) environment interacted with the apparatus via digital input–output hardware (PCI-6052E; National Instruments). Auditory stimuli were digitally generated by custom-built software and delivered via a pair of speakers (K701; AKG) placed outside the grid walls of the behavior box. Sound calibration was conducted using a Brüel & Kjær ½" condenser microphone with a preamplifier 2669 situated at the cat’s head. The system frequency transfer function was flat up to 32 kHz (±6 dB). A video camera and photoelectric sensors were used to monitor the cat’s position and movement.

2.2. Psychophysical training procedure

Using a method similar to our previous studies [29–32], we trained 9 cats to detect a tone pip of 4 kHz. The cats were deprived of food to 70–80% of their free-feeding body weight, but had free access to water. Initial training focused on shaping the cats to stand ready in front of a metal pipe waiting for the presentation of a tone pip. As illustrated in Fig. 1A, a tone pip was presented after the cats had kept their head in position for several seconds (randomly selected between 1 and 4 s across the trials). The original settings of tone stimulus were 4 kHz, 60 dB and 10 ms long with a 5 ms linear ramp. If the cats licked the metal pipe within 3 s, they would obtain a drop of liquid food. This was recorded as a hit trial. If they did not lick within 3 s, it was recorded as a miss trial. The cats usually had the habit of repetitively licking the tube at irregular intervals no matter whether the food reward was present or not. Trials with voluntarily licking before the tone presentation were aborted, and the cats had to return to the starting position to wait for a new trial; however, some recorded hit trials may also have been due to the cat’s voluntarily licking rather than an active response to tone presentation. To correctly evaluate the cat’s performance, we measured the rate of voluntary licking by randomly turning off the tone presentation in some trials and recording the cat’s response. In such a tone-absent trial (Fig. 1B), if the cat licked after the presumed tone presentation, it was recorded as a false-alarm trial, otherwise it was recorded as a correct rejection. The results of tone-absent trials were used to adjust the cat’s performance observed in tone-present trials. For this, we tested the cats with a 100-trial session, in which 50 tone-absent and 50 tone-present trials were randomly mixed, and the subjects’ performance was quantified via measure d′ from signal detection theory [33,34]. The d′ is calculated as $d' = Z(\text{hit-rate}) - Z(\text{false-alarm-rate})$, where $Z$ represents $Z$-transform of the probability of hit and false-alarm responses. $Z$-transform calculates the inverse of the normal cumulative distribution with a mean of 0 and standard deviation of 1. Cats demonstrated a reliable response to detect the tone within 50 sessions by reaching a $d'$ value of 2.0 for 5 consecutive sessions, after which they received electrode implantation.

![Fig. 1. Scheme of tone-detection task and power spectrum of tone pip stimulus.](image)

(A) Tone-present trial: after the cat’s head had been fixed in position for a while (1–4 s), a 4 kHz tone pip was presented, the cat licked a metal tube and obtained food reward. (B) Tone-absent trial: the sound output was turned off to measure the rate of voluntarily licking. (C) Power spectra showing the level of 40 and 5 dB tones relative to noise floor of the experiment setup.

2.3. Surgical preparation and electrode implantation

The cats were anesthetized by sodium pentobarbital (30 mg/kg) and fixed to a stereotaxic frame (SN-3N; Narishige). The position of A1 was marked on the bone surface according to stereotaxic coordinates. Four small holes were drilled over the occipital bone and fine jeweler’s screws were inserted to serve as an anchor for a metal block that was cemented to the skull with dental acrylic. After the cement had hardened, the head was held through the metal block and the ear bars were removed. We then drilled several small holes (0.5–1 mm diameter) in the temporal bone above the potential location of A1. A tungsten microelectrode (diameter: 250 μm; impedance: 2–5 MΩ at 1 kHz; FHC Inc.) was advanced into the cortex using a micromanipulator to examine the neural responses to tonal stimuli at each site. According to the characteristics of the tonotopic gradient, we identified the location of A1. We then implanted a microwire array following the method developed by Jackson and Fetz [35]. The microwire consisted of 12 (2 x 6) Teflon-insulated 50-μm diameter tungsten wires (part #795500; A-M Systems, Carlsborg, WA) running inside polymide guide tubes of 225-μm internal diameter (part #822200; A-M Systems). The tip impedance of each wire was around 0.5 MΩ at 1 kHz. For implantation, a 5 mm x 3 mm craniotomy was made at the location of A1 with a dental bur. The microwire array was then lowered into position using a custom-made manipulator so that the ends of the guide tubes rested just above the dura mater over the low frequency (<16 kHz) area of A1. Wires were inserted into the cortex until the tips of the electrodes were 1.0–2.0 mm below the dura, while viewing through a microscope and listening to an audio monitor of the recorded
The craniotomy was filled with SILASTIC, a silicone elastomer (World Precision Instruments) and sealed using dental acrylic. Plastic casing was attached with further skull screws and cement.

2.4. Electrophysiological recording and behavioral observing

The recording experiment started after 1–2 weeks of postoperative recovery. The physiological recording was conducted while the free-moving cats were conducting the tone detection task in the behavioral box. The microphone output was connected to a multi-channel preamplifier (RA16PA; TDT, Alachua, FL) using a flexible, low-noise cable. The output of the preamplifier was delivered to a digital signal processing module (RX-7; TDT). Action potentials from individual neurons were detected and sorted using the OpenEx software of TDT (Spikedetec). The threshold to detect a spike was set at 4SD of the system noise. Principal component analysis (PCA) was used to automatically select the features of detected spikes and create feature vectors. PCA searched for an ordered set of orthogonal basis vectors, the principal components, which captured the directions in the data of largest variation. A smaller subspace created by some of the initial principal vectors was then used to make an approximate projection of the data. In this projection, clusters of different units in the data, corresponding to separate neurons, were revealed [36,37].

In the recording sessions we tested the cats using two experiments. Experiment 1 was a 100-trial session including 50 tone-absent trials and 50 trials of 5, 10, 20, 30 and 40 dB tone pipes (4 kHz, 10 ms duration). The tone level was relative to the ambient noise floor. Fig. 1C shows the power spectrum of 5 and 40 dB tone pipes, which was recorded from a Bruel & Kjær 1/2″ condenser microphone with a preamplifier 2669 situated at the position of the cat’s head. This experiment was to test the cat’s performance in detecting pure tones at different intensities in a silent environment. Experiment 2 was to test the masking effect of noise on tone detection by presenting 50 trials of noise and tone and 50 trials of noise. The noise had a duration of 320 ms with a 5 ms linear ramp, and started 160 ms before the beginning of tone delivery. The noise signal was generated by the MATLAB program using inverse fast Fourier transform (IFFT), which covered a frequency range from 128 to 16,000 Hz with random phases. The root mean square level of noise matched a peak-to-peak level of 4 kHz pure tone. The target tone was 4 kHz, 40 dB and 10 ms. The session with 50 trials of silence and 50 trials of tone was also recorded as a control. In daily experiments, the cat’s motivation to obtain food reward gradually decreased, resulting in a decrease of performance. To avoid this effect, we tested the cats in different orders of recording sessions each day, and terminated the experiment as soon as the percentage of the cat’s lick response in tone-present trials dropped below 75%. For this reason, the total numbers of recorded neurons were different across the stimulus conditions.

At the end of all the experiments, the animal was deeply anesthetized and perfused with 10% formalin. The cerebral cortex was cut into coronal sections and stained with neutral red. The recording sites were confirmed according to the lesions caused by the electrode tips. This report was based on the units from A1.

2.5. Data analysis

Spike activities were aligned along the onset time of tone stimulus, constructing a raster plot of each trial (Fig. 2A). The peri-stimulus time histogram (PSTH), counting the spikes across different stimulus conditions, was computed in 1-ms bin width. The PSTH was smoothed by Gaussian function with 5 ms SD to construct a spike

![Image](image-url)
density histogram. To illustrate the population response patterns of A1 neurons, we constructed a color-coded spike density histogram for each unit (Fig. 2C). For visualization purposes, the firing rates of each neuron were assessed by a normalized value of the Z-score [38]. For this, the firing rate was subtracted by the mean of the background firing rate (averaged across the 100 trials of 100 ms pre-stimulus period), and then divided by the standard deviation of the background firing rate. Dark blue in the plot indicates the mean background firing rate. Dark red indicates firing that is 4 or more standard deviations above the mean of the background firing rate.

To evaluate the cat’s performance in the detection of tones at different intensities, we adopted an “adjusted measure” of the proportion correct [39]: \( p = \frac{p_{\text{hit}}}{p_{\text{hit}} + p_{\text{false alarm}}} \). If the subject showed a lick response in all tone-present trials \( p_{\text{hit}} = 1.0 \), but not in any tone-absent trials \( p_{\text{false alarm}} = 0 \), the correct rate was 1.0, indicating perfect detection. The correct rate of detecting each tone (5, 10, 20, 30 and 40 dB) constructed the psychometric function of tone detection (circles in Fig. 2D).

To quantify the relationship between neural activity and the cat behavior on a neuron-by-neuron basis, signal-detection theory was used to compute a “neurometric” curve [33,40]. The neurometric curve relates the probability that an ideal observer can use a neuron’s spike activity to discriminate whether a tone is present or not. Each neurometric curve was calculated on a neuron-by-neuron basis. For each trial, the tone-evoked firing rate was counted over the 100 ms post-stimulus period. The firing rate of tone-absent trials was also counted after a presumed tone presentation. We pooled the firing rates from the tone-absent condition and one of the tone-present conditions into two distributions. Next, from these two distributions, a receiver-operating characteristic (ROC) curve was generated. The area under the curve represents the probability that an ideal observer could differentiate between tone-absent and tone-present conditions. This process was repeated for all intensities of tone stimuli. The probability values were then plotted as a function of the tone intensity to form a neurometric curve (crosses in Fig. 2D). The psychometric and neurometric curves were fit using a logistic function [41]. From the fitted functions, we calculated psychometric and neurometric detection thresholds as the intensity corresponding to the proportion of correct responses of 0.75 (dotted line in Fig. 2D).

The area under the ROC curve was also calculated from the data of the noise-masking task to estimate neural performance to discriminate a tone from the noise background. In this task, the ROC curve was based on the distribution of the firing rate in the 50 tone-present trials and 50 tone-absent trials, respectively. Similarly, the correct rate of the behavioral response was calculated by using the proportions of the lick response in the tone-present and tone-absent conditions.

3. Results

3.1. Experiment 1: neural activities of A1 and behavioral responses to tone pips at various intensities

We implanted 216 (18 x 12) electrodes in both hemispheres of the auditory cortex in 9 cats. We collected 120 single-unit spike activities while the cats were detecting the 4 kHz tone pips randomly presented at 5, 10, 20, 30 and 40 dB. These units were selected from A1, which was identified by the characteristics of the tonotopic gradient and histological observation. All the units from A1 were included in our analysis only if they showed a significant response to the 4 kHz tones at one of the tested tone intensities. A significant response was defined if the firing rate over a 100 ms post-stimulus period was higher than 2SD of the firing rate during the pre-stimulus period. Generally the single-unit neural responses in A1 increased with the increase of sound intensity, while the increasing patterns varied among different neurons. Several representative examples of the neural responses are present firstly.

Fig. 2A presents the spike raster plot of an example A1 neuron responding to 10 ms tone pips (shaded area) at different intensities. The spike density was obviously elevated after the presentation of 4 kHz tone, and the response strength was monotonically modulated by the change of tone intensity. Consequently, the neurometric curve of tone detection (see Section 2 for definition) increased with the increase of tone intensity (Fig. 2D), which was in parallel to the psychometric curve calculated from the cat’s behavioral performance (see Section 2 for definition). Although the detection performance of this neuron was better than that of the cat’s behavior at high tone intensities, they were similar at low intensities. The neurometric and psychometric thresholds (corresponding to 0.75 correct rate, dotted line) were 5.1 and 6.6 dB, respectively. The similarity in the thresholds suggests that the spike activity of this neuron partly accounts for the behavioral performance of tone detection; however, there were also some neurons whose spike activities did not match the cat’s detection behavior.

Fig. 2B presents a neuron which was elicited only by a tone louder than 30 dB. The estimated neurometric threshold was 23.2 dB, while the psychometric threshold was 18.2 dB (Fig. 2E). This result suggests that the cat could still detect low intensity tones without the response of this neuron. On the other hand, there was also a unit which was sensitive to all the tested tone intensities, even when the cat could not effectively detect tones lower than 20 dB (Fig. 2C and F). The psychometric threshold was 21.2 dB, while the neurometric threshold in this case was set at the lowest tested intensity, 5 dB. Hence, the correlation between the cat’s behavioral performance and single-unit activity varied among the A1 neurons.

We then present the population response pattern of A1 neurons to tone stimuli. Fig. 2G illustrates the color-coded spike density histograms (see Section 2 for details) of 120 A1 neurons, which were ranked according to their mean firing rate of 5 dB tone in ascending order from top to bottom. The tone duration is indicated by the horizontal bar at the bottom of each plot. It is clear that the activities of all the recorded A1 neurons were not modulated in tone-absent trials. When a 5 dB tone was presented, a small number of units were elicited and with the increase of tone intensity, the number of responsive units gradually increased. The detection thresholds obtained from the simultaneously recorded neural and psychophysical data are compared on a neuron-by-neuron basis in Fig. 3. Some neurons had neurometric thresholds that were comparable to the psychometric thresholds. Other neurons had neurometric thresholds that were better or worse than the psychometric thresholds, indicating neurons that were more or less sensitive than the cat’s behavior. Although the neuron distribution was scattered, there was no significant difference between the populations of neurometric and psychometric thresholds (paired t-test, \( p = 0.65 \)), and the two threshold measures highly correlated \( r = 0.76; p < 0.01 \); therefore, on average, the cat’s tone-detection behaviors were attributable to the neural activities of A1.

3.2. Experiment 2: effect of noise masking on the neural and behavioral response to tone pips

Next, we examined whether the tone-detection behavior could be interfered with when the neural response in A1 was suppressed. We added wideband noise to observe the masking effect on both the cat’s behavioral and neural responses. The results of an example neuron are shown in Fig. 4. As shown by the raster plot (Fig. 4A) and
spike density histogram (Fig. 4D), when the cat was presented with a tone (40 dB; 4 kHz; 10 ms) against a silent background, the firing rate was largely increased (vertical line at 160 ms represents the tone onset). At the same time, the cat showed good behavioral performance (Fig. 4G). The proportion of the lick response was 0.94 in the 50 tone-present trials and 0.16 in the 50 tone-absent trials. The adjusted correct rate was 0.89, according to the formula of $p_{\text{correct}} = [p(\text{hits}) + (1 - p(\text{false alarms}))]/2$ [39]. ROC analysis based on the distribution of the firing rate in tone-present and tone-absent trials (see Section 2 for details) indicated that the discrimination performance of this neuron was 0.86, which was similar to the behavioral performance (Fig. 4J).

When a noise of 10 dB was added, the neuron showed a transient response at the onset of noise, and the tone-evoked neural response in the middle of noise remained obvious (Fig. 4B and E, the three vertical lines represent the onset of noise, onset of tone and offset of noise, respectively). As for the behavioral response, the proportion of lick response increased to 0.48 in the
noise-only trials, but that in the noise + tone trials was 0.84 (Fig. 4H). The difference in the proportion of lick response indicates that the cat could still discriminate a 40 dB tone from a 10 dB noise background, but the false alarm rate was high. The calculated correct rate was 0.68. The deteriorated behavioral performance was well explained by the decreased neural performance (Fig. 4K). Furthermore, when the noise intensity was raised to 30 dB, the neural response to a tone pip was largely suppressed (Fig. 4C and F). At the same time, the proportion of the cat’s lick response was 0.68 in the noise-only trials and 0.8 in the noise + tone trials (Fig. 4I), suggesting that it was quite difficult for the cat to discriminate a 40 dB tone from 30 dB noise. Again, the decrease in behavioral performance was paralleled by the decrease in neural performance (Fig. 4L).
The population results are presented in Fig. 5. We collected 103 single-unit records when the cats were undergoing a test session including 50 tone-absent trials and 50 tone-present trials. Fig. 5A and B illustrates the color-coded spike density histogram of the tone-absent and tone-present trials, respectively. It is clear that A1 units were well elicited when only a tone was presented. As shown by the distribution histogram of behavioral performance in Fig. 5C, the cats achieved a good correct rate in all the sessions, detecting a 40 dB tone from a silent background (mean ± SD: 0.87 ± 0.04). When 10 dB noise was added, some A1 neurons were elicited while others were not (Fig. 5D). The scattered noise-evoked responses could not cover the transient tone-evoked responses (Fig. 5E). Accordingly, the cats’ behavioral performance was slightly decreased (Fig. 5F, 0.82 ± 0.06). When the noise level was increased to 30 dB, the tonal responses of most A1 neurons were overwhelmed by the strong noise-evoked responses (Fig. 5G and H). Some neurons still showed a tone-evoked response even in the presence of 30 dB noise (lower part in Fig. 5H). This may be because these neurons had higher sensitivity to 4kHz tone stimuli, because we found that the amplitude of the tone-evoked response under 30 dB noise masking was negatively correlated to the neurometric threshold for detecting 4kHz tone from a silent background ($r = -0.74, p < 0.01$). Even so, the attenuated response in the neuron ensemble corresponded to severely deteriorate behavioral performance (Fig. 5I, 0.67 ± 0.05).

We quantitatively compared the neural and behavioral performance on a neuron-by-neuron basis in the scatter plot of Fig. 6, which presents all the 409 records of 3 different stimulus conditions: silent vs. tone ($n = 103$); 10 dB noise vs. tone ($n = 167$) and 30 dB noise vs. tone ($n = 139$). We found that the cat’s behavioral performance was positively correlated with the neural performance to discriminate them ($r = 0.49, p < 0.001$).

### 3.3. Behavioral choice-related neural activity

Next, we examined whether the activity of A1 neurons is modulated by the cat’s behavior. This issue was usually investigated in previous studies using choice probability analysis [40–43]. For this, the values of the neural response are placed into one of two distributions, based on the subject’s different behavioral choices under the same stimulus condition. A ROC curve was then generated by measuring the overlap between these two response distributions. The area under the ROC curve, named the choice probability index, was used to estimate the probability at which the behavioral choice can be predicted from the neuronal responses. According to the signal detection theory, if a neuron’s choice probability index equals 0.5, it indicates that there is no relationship between a neuron’s firing rate and the subjects’ behavioral choices. If the choice probability index is >0.5 or <0.5, it indicates that firing rates are predictive of the subjects’ behavioral choices.

In our experiment 1, each neuron was tested by randomly presenting 5 different stimuli (5, 10, 20, 30 and 40 dB tones), and each stimulus was repeated 10 times. The small number of repetitions in the same stimulus made it unreliable to conduct choice probability analysis; however, in our experiment 2, each stimulus condition was repeated 50 times, and we therefore conducted neuron-by-neuron-based choice probability analysis of these data.

An example of the relationship between A1 neural activity and behavioral choice is shown in Fig. 7A and B; the data in this figure were derived from those shown in Fig. 4B. The neuron’s response was independent of the cat’s behavioral choice; that is, the neuron’s response during trials when the cat licked the tube under the noise + tone condition (grey data in Fig. 7A) was comparable to its response during trials when it did not lick (black data). The same result was observed under the noise-only condition (Fig. 7B). Hence, this neuron does not appear to be predictive of the cat’s behavioral choices.

This observation was quantified by choice probability analysis. Fig. 7C and D shows the choice probability index as a function of time under the noise + tone and noise-only conditions, respectively. In these figures, a solid horizontal line indicates the level of 0.5, and dashed horizontal lines indicate the p = 0.05 significance limit of the permutation test. The choice probability index did not significantly deviate from 0.5 under any conditions, indicating that neural activity was not modulated by the cat’s behavioral outcome. The same analysis was conducted on other neural data when the cats were discriminating a tone pip from noise. We selected 182 records with a behavioral correct rate <0.8 (43 of 10 dB noise, 39 of 30 dB noise), in order to ensure enough samples for any behavioral outcomes. The results are shown in Fig. 7E and F, plotting the percentage of neurons with choice probability indices that were significantly ($p < 0.05$, permutation test) above 0.5 as a function of time. As the graphs show, this value was never exceeded by more than 5%. This means that, overall, there were no significant differences in neural activity between trials in which cats licked or did not lick the tube under both noise + tone and noise-only conditions. These results suggest that the evoked A1 activity did not directly determine the animals’ choices in this task.

### 4. Discussion

#### 4.1. Improvement of experiment methods

The spike activities of AC neurons have been long investigated in various animal species by electrical physiologists; however, most previous experiments were designed to reveal the fundamental characteristics of neural activities in response to sound stimuli, in which the subjects only perceived the stimuli passively under anesthetized or awake conditions [21–28]. The large body of accumulated electrophysiological data frequently lacked corresponding psychological data about the behavior discrimination of animals. It is not always appropriate to explain the human psychological phenomenon by using animal electrophysiological results. To date, some studies have examined both neural and behavioral responses to auditory stimuli in the same species [30–32,39,44]; however, a caveat to these experiments is that the physiological and psychological results were not obtained simultaneously for the same animal. Although it was reported that behavioral context does not change the tuning of AC neurons, suggesting that neural activities
observed under passive listening conditions provide a valid measure of the representation of sound properties [45], other studies have shown that engaging in a task can suppress auditory responses [46], alter the structure of the spectrottemporal receptive field [47] and sharpen the spatial tuning of A1 neurons [48]. Recently, several studies have been performed successfully to examine neural coding and behavioral discrimination simultaneously in the same animal; and to examine the link between neural activity of A1 and acoustic perception [29,41,42]. Using a similar approach, we conducted this study to observe the behavioral of cats to detect pure tone, and to record the neural responses of A1. Our results more directly examine the potential association between A1 and acoustic perception.

4.2. Role of A1 in tone detection

Previous electrophysiological studies on the A1 of anesthetized or awake animals have reported the co-existence of monotonic and nonmonotonic neurons, whose firing rate monotonically or nonmonotonically increases with the increase of stimulus intensity [24,49–53]. In this study, to avoid the saturation of behavioral performance, we only tested low and moderate levels of tone (5–40 dB). Among the tested sound levels, most of the individual A1 neurons showed a monotonic increase of the firing rate (Fig. 2G). The intensity-dependent increase in A1 activity paralleled the increase of the cat’s behavioral performance in tone detection.

With the use of ROC analysis, we constructed the neurometric function and estimated the threshold for each neuron to detect a tone pip. Although the detection threshold of some individual neurons may deviate from the threshold of cat’s behavioral performance (Fig. 2E and F), on average, the neural threshold covaried with the behavioral threshold (Fig. 3), suggesting that the population activities of A1 are predictive of the cats’ behavioral performance. This result is consistent with the finding that the neural activity of the primary somatosensory cortex (S1) may play a role in representing the stimulus amplitude in the vibrotactile detection task [54].

We also investigated how the tone-detection behavioral and neural activities were affected by masking noise. The type of masking used in this study corresponds to energetic masking, involving noise that overlaps in frequency and time with the target, which is commonly thought to originate at a peripheral level, reflecting direct physical interactions between the signal and the masking noise within the cochlea [55]. Our results showed that the larger the difference between the neural activities of tone-absent and tone-present trials, the higher the cats’ performance to detect a tone (Figs. 4–6). This supports the idea that the differential cortical representations are the neural basis for behavioral discrimination. Similar results have also been reported; for example, Engineer et al. found that differences in A1 neural activity better predict word discrimination in rats [39]. A fMRI study of native and non-native English speakers reported that (as in rats) the distinctiveness of
the A1 activity patterns evoked by consonants was correlated with discrimination ability [56].

Previous lesion studies have demonstrated that the discrimination of simple sounds can be relearned after auditory cortex lesions [12–17], whereas the discrimination of complex sounds cannot be relearned [4,7,9–11]. This may suggest that AC is an essential structure for the processing of complex spectra-temporal patterns, but not for the processing of simple sound parameters. Such lesion experiments, however, typically examine an animal’s performance after recovery from ablation surgery. It is possible that reorganization of the central auditory system may enable the recovery of basic auditory functions after cortical ablation. A study has shown that the rats exhibited an acute and profound inability to detect tones, soon after applying the GABA agonist muscimol to reversibly inactivate the A1 of rats [18]. In the present study, we demonstrated a co-variation between the neural responses from the cat A1 and a subject’s detection of tones. Our results provide further evidence that A1 plays a role in simple acoustic perceptions, but its role may be compensable after lesions.

4.3. Neural signal of behavioral choices

We compared the neural responses of A1 during trials when the cat licked or did not lick the tube, and found that the neural activities of different behavioral choices were similar under both tone-absent and tone-present conditions (Fig. 7). This is consistent with several previous single-unit studies that examined the role of A1 in sensory encoding and decision making and reported that neural activity in A1 correlated best with elements of sensory encoding and was not modulated by the subjects’ behavioral decisions [29,41,42]. It has been proposed that A1 provides “sensory evidence” to inform the decision and brain areas outside AC, such as the ventrolateral prefrontal cortex (vPFC) and ventral premotor cortex (VPC), encode the output of the decision process [57,58].

On the other hand, human EEG, MEG and fMRI experiments have demonstrated that AC is modulated by the behavioral response of a subject [19,31,59–62]. For example, in a MEG study on human subjects detecting a stream of regularly repeating target tones against a background of masking tones, the detected target sounds elicited a prominent, long-latency response (50–250 ms), whereas undetected targets did not. This type of response was thought to originate from the non-primary auditory cortex. In contrast, both detected and undetected targets produced equally robust auditory middle-latency, steady-state responses, presumably from the primary auditory cortex [19]. These results suggest that the non-primary auditory cortex may contain decision associative neurons; however, Tsunada et al. recorded single neural activities from the secondary auditory cortex of monkeys and did not find the choice-related modulation of neural activity [42]. Thus, whether other regions of AC are involved in the subject’s behavioral choice is worthy of further investigation.

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