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2pAB10. Active listening in a complex environment

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Spatially-guided behaviors in echolocating bats depend upon the dynamic interplay between auditory information processing and adaptive motor control. The bat produces ultrasonic signals and uses information contained in the returning echoes to determine the direction and distance of objects in space. With this acoustic information, the echolocating bat builds a 3-D auditory representation of the world, which it uses to guide a suite of coordinated motor behaviors, including head and pinna movements, as well as the timing, duration, frequency characteristics and directionality of sonar signals. Adaptive echolocation behaviors shape the acoustic information available to the bat's sonar imaging system and provide a window to its perception of complex scenes. In a complex environment, an echolocating bat encounters multiple reflecting surfaces that return a cascade of echoes from each sonar transmission. The work presented here will focus on adaptive echolocation behaviors of the big brown bat as it tracks a selected prey item in the presence of multiple objects, both obstacles and other prey. Data suggest that bats can successfully segregate streams of echoes from closely spaced objects through finely tuned adaptive sonar signal control.

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I. INTRODUCTION

Echolocating bats emit high frequency vocalizations and process echo returns to obtain information about the location and features of objects in their surroundings (Griffin, 1958/1986; Griffin et al., 1960). In cluttered environments, a single echolocation call results in a cascade of sound reflections, arriving from different directions and at different times. Bats process complex echo cascades to accurately represent the location of closely spaced objects, evidenced by their agile maneuvers through cluttered environments, and yet perceptual representation of the world through biological sonar is not well understood. We hypothesize that perception by echolocation, like vision, builds upon transformational rules that support interpretation of the scene (Hoffman, 1998; Bregman, 1990; Moss and Surlykke, 2001). Furthermore, we hypothesize that ***adaptive vocal control*** over echo information obtained from the environment plays a key role in the bat's perception, permitting an elaborate representation of a dynamic auditory scene (Moss and Schnitzler, 1995; Moss and Surlykke, 2001, 2010; Moss et al. 2011).

Adaptive control of sonar call features is a hallmark of active sensing by echolocation. As a bat approaches an object, it continuously modifies the duration, timing, intensity, spectral characteristics and directional aim of its calls (Chiu et al., 2009, Ghose and Moss, 2003, Ghose et al., 2007; Moss et al., 2011; Moss and Surlykke, 2010). The bat's changes in sonar signal design influence information carried by echo returns and serve as an indicator of the task-specific information an echolocating bat is seeking. For example, long constant frequency (CF) or shallow frequency modulated (FM) signals produced by bats searching for insects are well suited for target detection, as sound energy is concentrated in a narrow frequency band over an extended period of time. Once an insect has been detected, bats typically increase the bandwidth of FM components to improve target localization in azimuth, elevation and range (Moss and Schnitzler, 1995). As the bat approaches the insect, it then decreases the inter-pulse-interval and pulse durations to maximize the information received about the insect's position in space. The animal's adaptive feedback control over sonar signal design depends on neural specializations that enable rapid and precise sensorimotor transformations (Moss and Sinha, 2003).

Our research exploits specializations of the echolocating bat, an animal that can negotiate a complex auditory world in complete darkness. For the echolocating bat, the analysis of auditory scenes builds upon its active production of sounds that reflect from objects in the environment. The bat adaptively adjusts the features of its sonar vocalizations in response to information obtained from echo returns. Therefore, the bat's behavioral control of its sonar vocalizations provides a window into its perceptual world. Importantly, the bat adjusts the direction and duration of its calls to probe information from different locations in space (Surlykke et al., 2009; Moss et al., 2011), and this vocal-motor control provides a measure of the animal's acoustic gaze.

II. METHODS

Big brown bats (*Eptesicus fuscus*) are engaged in a target tracking experiment to study adaptive motor behaviors in open and cluttered environments. Bats are trained to rely on echolocation to track a moving food reward while resting on a platform (Fig. 1A). We have collected data that demonstrate the bat's active control over sonar call production as it tracks objects in a complex sonar scene.

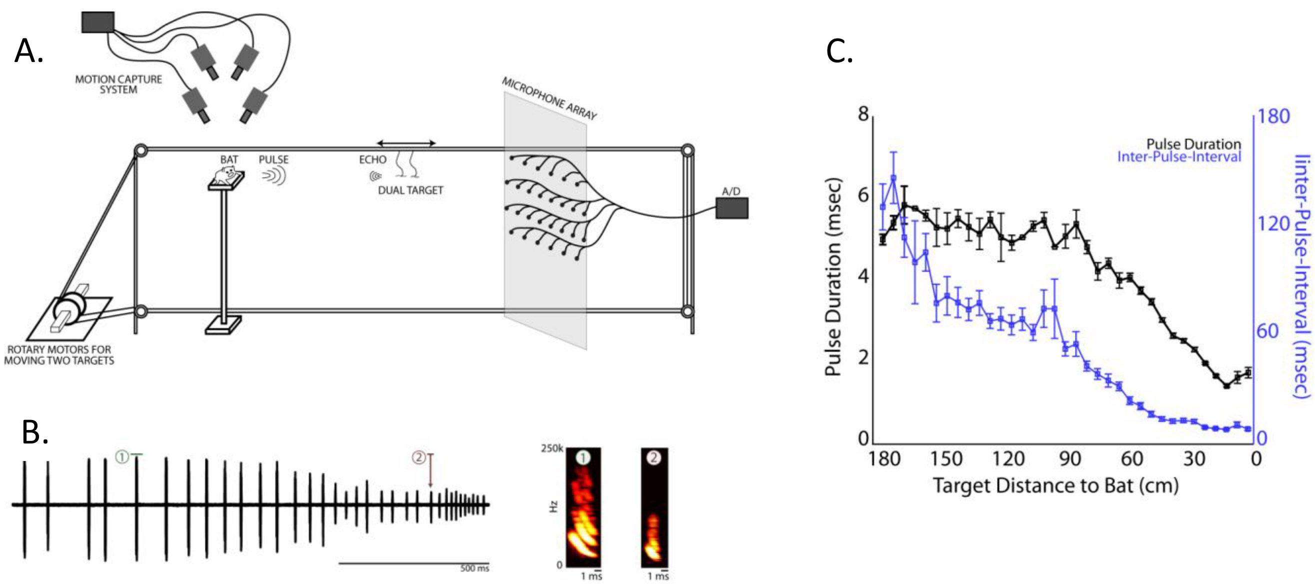

Figure 1. A. Schematic of the laboratory setup for recording echolocation vocalizations while a bat tracks one or more moving targets (Adapted from Aytekin et al., 2011). The bat is trained to sit on a platform and wait for a tethered insect to approach, while a microphone array captures the bat's sonar vocalizations. High speed video cameras record the bat's head and pinna position as it performs the task. In some trials, multiple targets approach the bat at different speeds; obstacles are also sometimes introduced along the path of the tethered insects.

B. Oscillogram (left) and spectrogram of highlighted pulses (right) of one recorded sequence of echolocation signals produced by the bat as it tracked a moving target. Call duration, pulse interval, and spectral features change with target distance.

C. Sonar call duration (black, left ordinate) and interval (blue, right ordinate) of the bat's sonar calls change as the target approaches from a starting distance of 180 cm.

We have also used a 28 channel microphone array to characterize the bat's 3D sonar beam pattern as it tracks moving prey. This microphone array is placed just beyond the targets and distractors in the behavioral tracking set-up (see Fig. 1A). Signal processing algorithms for noise compensation, spectral analysis and 3-D data reconstruction have been established. Additionally, since the experimental results are very sensitive to the position of the microphones, a method to automatically calibrate the microphone positions has been developed. For noise removal, wavelet based de-noising algorithms are used.

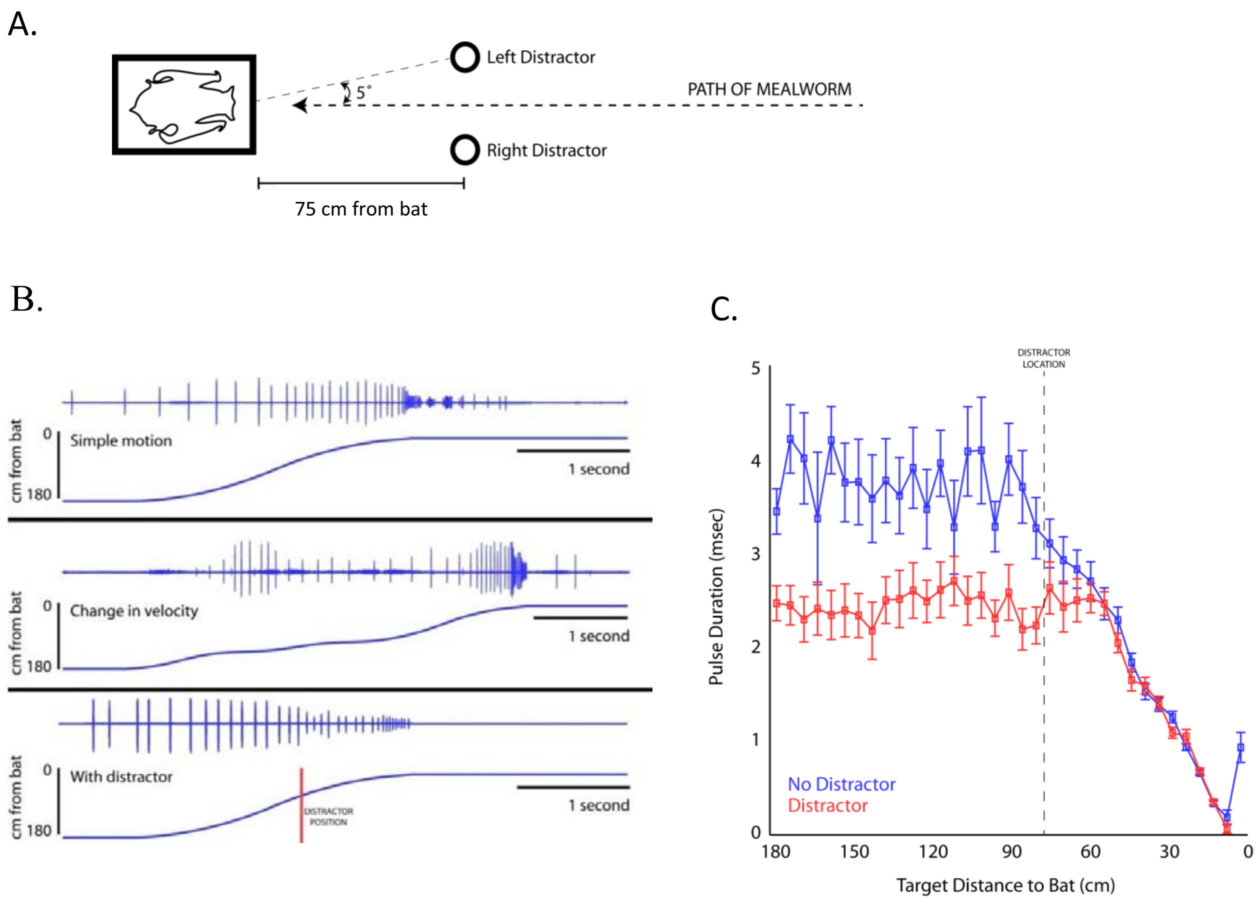

Figure 2. A. Schematic illustration of target tracking task with the introduction of distractors along the path of target motion. B. Different paths of motion introduced in the target tracking task evoke different patterns of echolocation call design. C. The presence of a distractor along the path of the target influences the duration of echolocation calls. When a distractor is introduced, the duration of the calls is adjusted to the closer of the objects.

III. RESULTS

Echolocating bats make adjustments in the features of their sonar signals as they track moving targets (see Figures 1C and 2C). These changes provide a window into the acoustic information the bat has processed as well as information the bat is seeking. Here we report on adjustments in sonar beam pattern, duration and pulse interval as the bat tracks single and multiple targets, in an open environment and in the presence of distractors.

Figure 3 compares the sonar beam pattern of a bat's call at 60 kHz as it tracked a moving prey item in an open room (left) and in the presence of a distractor (right). Note that the bat sharpens the central region of the sonar beam when the target is adjacent to a distractor.

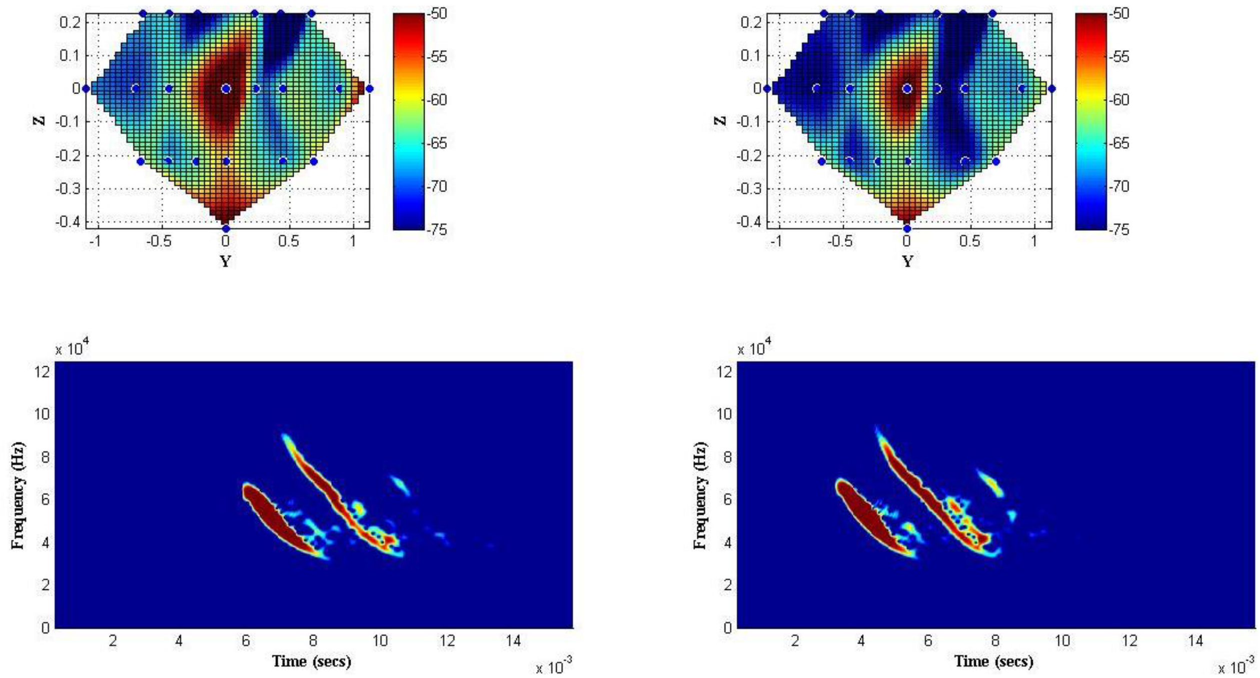

Figure 3. Examples of sonar beam patterns at 60 kHz (above) and spectrograms (below) of single calls produced by the bat in the target tracking experiments. The signal displayed on the left was recorded while the bat tracked the moving prey item in the open environment, and the signal on the right was recorded in the presence of a distractor at a distance of 75 cm from the bat (Krishnan et al., 2012).

We have also performed experiments in which two different targets approach the bat. In some trials, both targets approach in parallel at the same velocity, while in other trials the targets start and end motion towards the bat at different times. The bat's sonar behavior, head and pinna movements are recorded throughout each trial. We have found that in trials in which two targets approach the bat at different velocities, we can determine which of the two targets that bat selectively attended based upon changes in sonar pulse duration and inter-pulse-interval (Figure 4). For those trials in which the bat attacked the target approaching at a higher speed, the bat makes an earlier adjustment in call duration and interval (Figure 4, data plotted in black); whereas the bat made these adjustments the temporal features of calls later in the trial when it was tracking the slower moving target (Figure 4, data plotted in red). These results demonstrate how the bat's adaptive vocal behavior can be used as an indicator of where in space the bat is directing its attention.

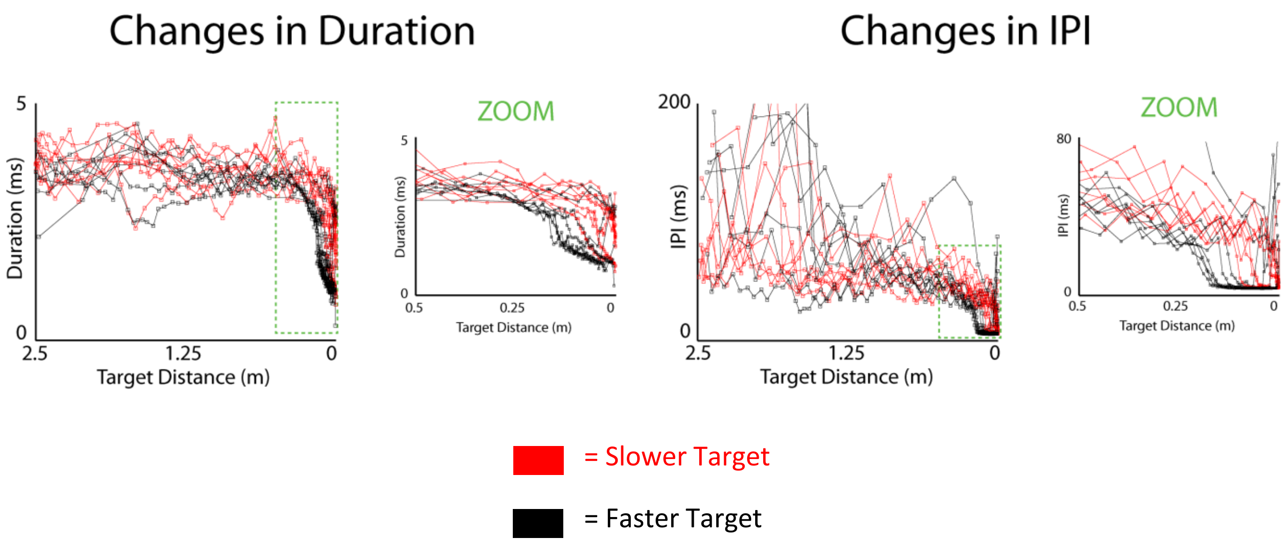

Figure 4. Left. Changes in a bat's sonar pulse duration as it tracks two approaching targets, tethered insect prey. Red indicates trials in which the bat intercepted the slower of two moving targets, and black trials indicate trials in which the bat intercepted the faster target. Right. Changes in pulse interval during tracking of two targets moving through space. Colors indicate bat's target selection, as described in text.

IV. DISCUSSION

The experiments described here were designed to determine how the bat adjusts the acoustic characteristics of its sonar pulses, and the positions of its head and ears, to efficiently localize targets in the environment. We find that the bat adjusts changes in sonar pulse production and echo reception to maximize the information it receives from the environment. We report here that the bat actively shapes its representation of the acoustic scene to bolster the sensory signals associated with a selected target and attenuate those associated with obstacles.

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