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Improved sleep–wake and behavior discrimination using MEMS accelerometers

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Abstract

State of vigilance is determined by behavioral observations and electrophysiological activity. Here, we improve automatic state of vigilance discrimination by combining head acceleration with EEG measures. We incorporated biaxial dc-sensitive microelectromechanical system (MEMS) accelerometers into head-mounted preamplifiers in rodents. Epochs (15 s) of behavioral video and EEG data formed training sets for the following states: Slow Wave Sleep, Rapid Eye Movement Sleep, Quiet Wakefulness, Feeding or Grooming, and Exploration. Multivariate linear discriminant analysis of EEG features with and without accelerometer features was used to classify behavioral state. A broad selection of EEG feature sets based on recent literature on state discrimination in rodents was tested. In all cases, inclusion of head acceleration significantly improved the discriminative capability. Our approach offers a novel methodology for determining the behavioral context of EEG in real time, and has potential application in automatic sleep–wake staging and in neural prosthetic applications for movement disorders and epileptic seizures.

Keywords: State; EEG; REM; Slow wave; Vigilance; Classification; MEMS; Accelerometer

1. Introduction

There is a long history of determining the state of vigilance for humans (Broughton, 1999) or animals (Robert et al., 1999) using EEG criteria. Nevertheless, there is considerable uncertainty when determining the state of vigilance using EEG alone. Therefore, EEG is typically augmented with simultaneous visual behavioral monitoring, and/or the incorporation of electromyogram (EMG) or electrooculogram (EOG) recordings.

We are developing the technical capability for discriminating state of vigilance in real time. Our objective is to provide contextual input for seizure prediction and control. It is readily accepted that the dynamics of EEG change remarkably in the different stages of wakefulness and sleep (Niedermeyer, 1999). Yet much of the current work in seizure detection and prediction (Mormann et al., 2005) focuses on statistical or dynamical changes of the EEG with respect to a baseline defined without regard to state. Our end goal is to implement state-dependent seizure detection and control in medical devices suitable for human implantation during the activities of daily living, where continuous video monitoring would not be feasible and EMG or EOG electrodes might be invasive or cumbersome.

In this study, we explored combining head acceleration measurements with EEG in order to improve our ability to discriminate state of vigilance in rodent experiments. We incorporated biaxial dc-sensitive microelectromechanical system (MEMS) accelerometers into the head-mounted preamplifier circuit used for EEG recording. We used combined EEG and behavioral video to establish training and validation data sets, and then used EEG features with and without accelerometer features in a multivariate linear classifier. We tested a broad range of EEG feature sets based on those used in the recent literature for state discrimination in rodents (Robert et al., 1999). Our approach offers a novel methodology for determining the

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behavioral context of EEG in real time. Preliminary results of this investigation were previously reported (Peixoto et al., 2004; Sunderam et al., 2005).

2. Methods

2.1. Surgical implantation and data acquisition

Video (3 fps including visual and infrared sensitivity), EEG and head acceleration were recorded continuously from adult male Sprague-Dawley rats 200–300 g in weight (Harlan Ltd., NY) using a custom-made electronics and acquisition system (Labview, National Instruments Ltd.).

Head-mounted preamplifiers were constructed with integrated dc-sensitive biaxial MEMS accelerometers (ADXL 311, Analog Devices Ltd.; sensitivity of 312 mV per g, where g = acceleration due to gravity, at the reference voltage of ±5 V, range $\pm 2\,g$, configured for 0–100 Hz response, Fig. 1). The MEMS chip and requisite elements for signal transduction (two capacitors and one resistor), occupy a small fraction of surface area on the circuit board shown in Fig. 1. The remainder includes the EEG preamplifier and additional elements for simultaneous electrical stimulation and recording. The minimum additional surface area required to incorporate such an accelerometer into a final production headstage is approximately 0.3 cm^2. The head-mounted preamplifier was mechanically and electrically attached to the animal's head through a Plastics-One (Roanoke, VA) 363 series connector. EEG was available from two cortical surface electrode (0–80 stainless steel screw) pairs (Bregma-referenced stereotaxic coordinates from Paxinos and Watson, 2004: ML ±3.0 mm, AP +0.5 and −0.75 mm) and two depth electrodes (bipolar pairs, 125 μm stainless steel wires, ends staggered by 300 μm) placed bilaterally in the dorsal hippocampus (AP −2.5 mm, ML ±2.0 mm, DV −2.75 mm). Head acceleration was measured along orthogonal axes in the sagittal plane of the animal's head by the accelerometer (Fig. 2). The EEG and acceleration signals were sampled at 2 kHz and stored as 16-bit signed integers in contiguous, 1-h long files.

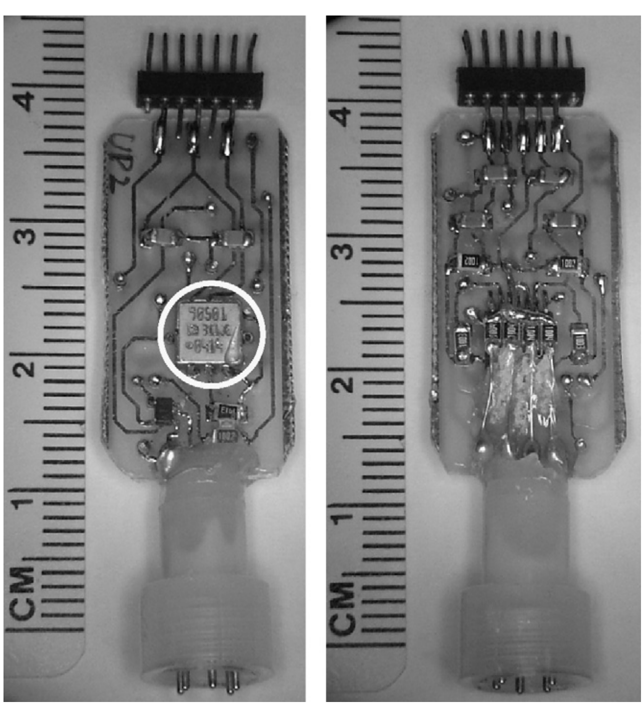

Fig. 1. Front (left) and back (right) views of a head-mounted circuit for EEG preamplification with MEMS biaxial accelerometer (circled). Terminals at the bottom plug into a pedestal on the rat's head.

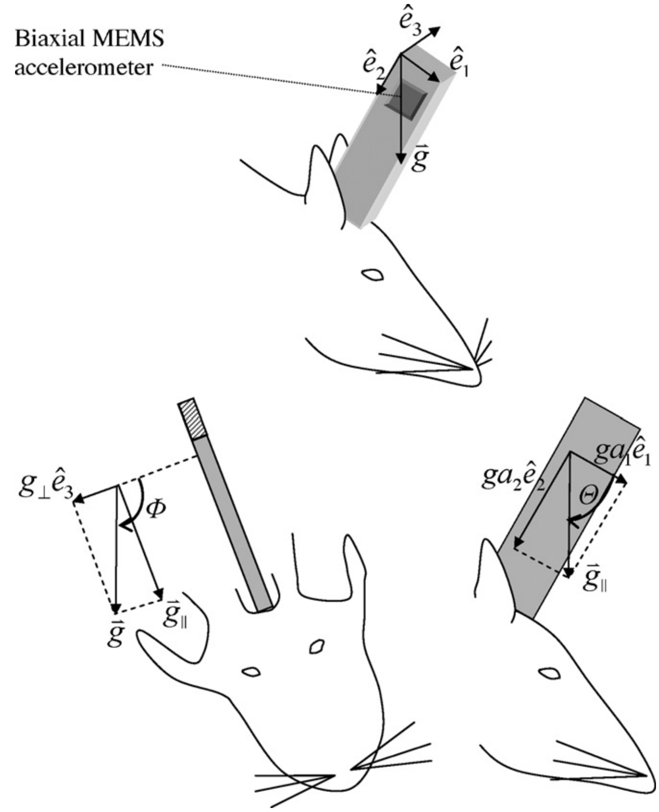

Fig. 2. Schematic of accelerometer axis orientation with respect to animal's head (upper) and Cartesian axes used to estimate angles of head tilt with respect to gravity (lower). Head acceleration variables A_1 and A_2 are measured along axes $\hat{e}_1$ and $\hat{e}_2$ in the plane of the MEMS chip surface which is in the sagittal plane of the rat's head. The static components (f < 1 Hz) of A_1 and A_2 are due to gravity $\vec{g}$, which allows us to measure the angle Φ between the interaural axis $\hat{e}_3$ and gravity, and the rotation angle, Θ, of the head about the interaural axis.

The animals were monitored for up to 7 days in a circular chamber (20 in. diameter) with free access to food and water. Artificial lighting followed a 12 h on–off light–dark cycle, and was supplemented with infrared illumination at 940 nm from photodiode arrays, to allow for continuous video monitoring. We chose infrared illumination because rats are insensitive to light for wavelengths above 650 or 700 nm (see for example, Aggelopoulos and Meissl, 2000; or Jacobs et al., 2001), and video cameras sensitive to this wavelength are readily obtainable. All procedures were approved beforehand by the IACUC of George Mason University.

2.2. Visual expert scoring of state

An EEG expert (SLW) inspected video and EEG to label sequential, non-overlapping epochs of 11 h of recording from