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Event-related potential measures of gap detection threshold during natural sleep

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HIGHLIGHTS

- Event-related potentials were used to provide an estimate of the gap detection threshold during sleep.
- Gap detection thresholds could be accurately estimated while the subject was awake using the amplitude of N1, peaking at about 100 ms and also during stage N2 of sleep using the amplitude of P2, peaking at about 200 ms.
- Only larger suprathreshold gaps were able to elicit N1 and P2 during REM sleep.

ABSTRACT

Objective: The minimum time interval between two stimuli that can be reliably detected is called the gap detection threshold. The present study examines whether an unconscious state, natural sleep affects the gap detection threshold.
Methods: Event-related potentials were recorded in 10 young adults while awake and during all-night sleep to provide an objective estimate of this threshold. These subjects were presented with 2, 4, 8 or 16 ms gaps occurring in 1.5 duration white noise.
Results: During wakefulness, a significant N1 was elicited for the 8 and 16 ms gaps. N1 was difficult to observe during stage N2 sleep, even for the longest gap. A large P2 was however elicited and was significant for the 8 and 16 ms gaps. Also, a later, very large N350 was elicited by the 16 ms gap. An N1 and P2 was significant only for the 16 ms gap during REM sleep.
Significance: ERPs to gaps occurring in noise segments can therefore be successfully elicited during natural sleep. The gap detection threshold is similar in the waking and sleeping states.

1. Introduction

1.1. Gap detection thresholds

Temporal resolution refers to the ability to detect rapid changes in a sound envelope, an ability thought to be critical for the perception of speech and the localization of sound. Temporal resolution is often studied using gap detection methods in which a silent period (or "gap") is inserted in a long duration auditory stimulus. The minimum time interval between two stimuli that can be reliably detected provides a measure of the gap detection threshold. There is general agreement that normal-hearing young adults can detect 3–5 ms gaps in moderately loud continuous white noise although this is influenced by a number of factors including the intensity and frequency of the stimulus in which the gap is inserted and the duration of this stimulus (Moore, 1997; He et al., 1999; Samelli and Schochat, 2008). Temporal processing is poorer in children with language delay and in those with aphasia, dyslexia or central auditory processing disorder (Farmer and Klein, 1995; Phillips et al., 2010). There may also be a decline in gap detection threshold in the elderly (Schneider and Hamstra, 1999; Ross et al., 2010; Harris et al., 2010, 2012; Lister et al., 2011).

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The usual gap detection testing procedures require the active participation and co-operation of the observer. Certain individuals, for example, infants, young children and the senile may either be unable or unwilling to continually focus attention on the detection task during the relatively long testing interval. In these cases, event-related potential (ERP) procedures can be used to obtain a so-called "objective" estimate of gap detection. In young adults, the presentation of a gap occurring in a long duration stimulus elicits a negative component, N1, peaking at about 100 ms after the onset of the gap (offset of the stimulus), followed by a smaller amplitude positive component, P2, peaking at about 180–200 ms (Michalewski et al., 2005; Pratt et al., 2005, 2007; Lister et al., 2007; Ross et al., 2010; Palmer and Musiek, 2013). The amplitude of N1 gradually decreases as the duration of the gap decreases and a reliable N1 can still be elicited by gaps that exceed 5 ms (Pratt et al., 2005; Atcherson et al., 2009; He et al., 2012).

1.2. The effects of sleep

In spite of the potential benefit of ERP methods for the objective detection of gap thresholds, they have not often been employed in clinical populations. This is because the recording of ERPs from wakeful participants also requires extensive co-operation for relatively long periods of time in order to reduce movement and blinking artifact. This is often not possible in the very cases for whom objective ERP measures of gap detection might be most useful. An ideal setting in which ERPs can be recorded for long periods of time without concern for artifact is during natural sleep. Long latency ERPs such as N1 and P2 are however markedly affected by sleep (see Campbell and Colrain, 2002; Colrain and Campbell, 2007 and Czisch et al., 2009 for reviews). Campbell and Macdonald (2011) recorded ERPs to 20 ms gaps occurring in 1.5 s duration white noise segments during all-night sleep. The intensity of the white noise segment was either 60 or 80 dB peak Sound Pressure Level (SPL). N1 was at or near baseline level during non-REM (NREM) sleep and much attenuated during REM sleep compared to the waking state. A later P2 was however much larger during NREM and somewhat larger during REM sleep compared to that recorded in the waking state. Thus, although the morphology of the N1 and P2 components did differ between the waking and sleeping states, a distinct gap-elicited neural response remained visible. In addition, a very large amplitude negativity, peaking at about 350 (the "N350"), was visible following the presentation of the gap occurring the 80 dB SPL segment.

1.3. The purpose of this study

Although Campbell and Macdonald (2011) have demonstrated that gap-elicited ERPs are clearly discernible in the sleeping subject when a long supra-threshold duration gap is embedded in an auditory stimulus, it is not known whether this would be the case as the duration of the gap approaches threshold width. The present study varied the duration of the gap from below threshold (2 ms) to well above threshold levels (16 ms).

2. Methods

2.1. Subjects

Twelve self-reported good sleepers (6 females) between the ages of 21 and 25 years spent a single night in the sleep lab. None had a history of neurological or psychiatric disorder. Normal hearing was verified to be within 15 dB ISO for 500, 1000, 2000 and 4000 Hz frequencies. Subjects were asked to refrain from caffeine and alcohol use in the 24 h prior to testing. Subjects signed a consent form and received an honorarium for participation in this study. The study was conducted according to the guidelines of the Canadian Tri-Council (Health, Natural and Social Sciences) on ethical conduct involving human subjects. Two of the subjects were frequently awakened by the stimulus and their data were thus rejected from further analyses.

2.2. Stimuli and procedure

A 70 dB peak SPL 1500 ms duration (rise-and-fall 5 ms) auditory white noise segment was presented monaurally to the right ear through EAR-3A foam insert earphones. The spectral content of the noise was flat (within 10 dB) across the 100–10,000 Hz frequency range. Equally probable and randomly occurring 2, 4, 8 or 16 ms gaps were introduced 1000 ms after stimulus onset. The gap had a square onset and offset. The noise segment was presented every 3 s. A total of 200 stimuli were presented within a block lasting 10 min.

The waking data were collected from 21:00–23:00. In the waking state, subjects were asked to read a book or magazine of their choice and ignore the auditory stimuli. Horizontal eye movements were monitored to assure compliance with these instructions. After completion of the physiological recording, subjects were engaged in a behavioural task in which they were asked to signal their detection of the gap by button pressing. On 20% of trials, no gap was presented while a 2, 4, 8 or 16 ms gap was presented with equal probability on the remaining 80% of trials. Order of presentation of the different duration gaps was randomized. In total, 100 trials were presented (i.e., 20 each of the 0, 2, 4 8 and 16 ms gaps). Subjects were permitted to sleep at 23:30.

At least 3 blocks of stimuli were presented in definitive wakefulness, stages N2 (former stage 2) and REM of sleep. Sleep stages were classified in real-time by an experienced sleep researcher. Only blocks in which the subject did not change sleep stage (i.e., the entire block consisted of a homogenous stage of sleep) were retained for further analysis. If there was evidence of arousal or movement, stimulus presentation was paused and only resumed again if the subject returned to the same stage of sleep. If a change of sleep stage was observed within the block, all data were rejected. The sleep stage scoring was later verified by other scorers (see details below). Time between stimulus presentation blocks was approximately 20 min. There were sufficient data to permit the analysis of at least 3 blocks of data for all subjects in stage N2 and for 8 of the subjects in stage REM. Two blocks of stimuli were analyzed during stage REM for the other 2 subjects. There were insufficient data for the analysis of the data during stage N3 (former stages 3 and 4). Previous studies have however indicated that the N1 and P2 components vary minimally between stages N2 and N3.

2.3. Physiological recordings

The EEG was recorded from Fz, Cz, Pz and Oz using silver/silver chloride electrodes and referenced to the tip of the nose. The occipital electrode placement was employed to assist in the determination of sleep onset. Vertical eye movements and blinks were recorded from electrodes placed at the infra- and supra-orbital ridges of the left eye. A horizontal EOG was recorded from electrodes placed at the outer canthus of each eye. The ground electrode was located on the forehead. Inter-electrode impedances were below 2 kOhms for the EEG electrodes and below 5 kOhms for the EOG electrodes. The physiological signals were amplified with a bandpass of 0.03–35 Hz. The 0.03 Hz high-pass filter corresponded to a time constant of 5 s. The physiological signals were continuously digitized at a 256 Hz sampling rate and stored on hard disk for later off-line analyses.