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Highly relevant stimuli may passively elicit processes associated with consciousness during the sleep onset period

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ABSTRACT

Sleep onset marks the transition from waking to sleep, during which conscious awareness of the external environment is gradually lost. The present study examines the extent of processing of acoustic change during sleep onset. An auditory optimal paradigm was used to record event-related potentials to six deviant stimuli during wakefulness, stage N1, and stage N2 sleep. During waking and early-stage N1, two of the deviants, environmental sounds and white noise, elicited a P3a reflecting processes that may lead to conscious awareness of acoustic change. Surprisingly, the P3a was also observed following both deviants during late-stage N1, a period thought to represent decreased awareness of the environment. Only the environmental sounds continued to elicit a P3a during stage N2 sleep, associated with the loss of consciousness of the external environment. Certain auditory stimuli may thus continue to activate processes that may lead to conscious awareness during the sleep onset period.

1. Introduction

A number of neuroscience methods have been proposed to study the process by which individuals can become conscious of the external environment during apparently unconscious states (for reviews, see Koch, Massimini, Boly, & Tononi, 2016; Tononi & Laureys, 2009; Massimini, Boly, Casali, Rosanova, & Tononi, 2009). In this context, consciousness can be defined as “awareness” of external environmental events. During states such as coma, general anaesthesia, and natural sleep, the individual appears to be profoundly unaware of their external environment (for reviews, see Morlet & Fischer, 2014; Sanders, Tononi, Laureys, & Sleight, 2012).

The present study examines the extent of processing of acoustic change during the sleep onset period, a period of time when awareness of the external environment is gradually lost. In order to study acoustic change, an unchanging homogeneous, frequently occurring auditory stimulus is presented rapidly. At times, this stimulus is changed. The brain is equipped with mechanisms capable of rapidly detecting acoustic change and taking appropriate action should the need arise. The detection of acoustic change may be critical for survival. The sleeper must evaluate all incoming stimuli for potential relevance, such as biological and/or personal information (e.g. a very intense stimulus, the interruption of breathing, a baby’s cry), in order to force an awakening to take appropriate action. Yet for sleep to be of benefit, it needs to remain as undisturbed as possible, and only interrupted when the stimulus input is potentially highly relevant. Therefore, even during sleep, a decision must be made about whether new stimulus input is so highly relevant and critical that it requires an arousal to wakefulness, or whether it is, in fact, irrelevant allowing sleep to remain undisturbed.

Sleep is not a uniform state. It consists of a series of sub-stages. Changes in EEG frequency bands and other physiological signals,

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especially eye movement (EOG) and muscle (EMG) activity, are used to differentiate between these sub-stages. During wakefulness, the EEG shows low amplitude, high frequency (> 15 Hz) beta activity and lower frequency (8–12 Hz) alpha activity. Non-REM (NREM) sleep can be subdivided into stages N2 and N3 and the EEG is mostly dominated by high amplitude, lower frequency theta (4–7 Hz) and delta (0.5–3 Hz) activity (for a review, see Scammell, Arrigoni, & Lipton, 2017).

The sleep onset period, largely involving what is called stage N1 sleep, is characterized by a reduction in the relative amount of beta and alpha activity, and the appearance of slower theta waves compared to wakefulness. A number of other physiological changes are also apparent, such as rolling eye movements, changes in heart rate, respiration, muscle tonus, and temperature. Foulkes and Vogel (1965) observed the presence of dream-like mentation during the pre-sleep waking period in which the EEG was dominated by alpha activity. They suggested that the onset of the transition into sleep might precede the traditional stage N1 classification of sleep onset. Because of the numerous physiological and psychological changes, the definition of actual sleep onset is somewhat problematic. Some researchers employ a behavioural definition of sleep onset. Thus, subjects are said to be asleep when they no longer are able to respond to external target stimuli. Subjects are still capable of overtly responding to external stimuli in what has been traditionally defined as stage N1 according to physiological criteria (Bastuji, García-Larrea, Franc, & Mauguière, 1995; Colrain, Di Parsia, & Gora, 2000; Colrain, Webster, Hirst, & Campbell, 2000; Cote, De Lugt, & Campbell 2002; Johnson, Hanson, & Bickford, 1976; Ogilvie, Simons, Kuderian, MacDonald, & Rustenburg, 1991), although lapses in performance and the presence of micro sleeps are often observed (Williams, Tepas, & Morlock, 1962). Overt responses are rare during stage N2 sleep. For this reason, the appearance of phasic events associated with stage N2 (e.g. K-Complexes and spindles) have often been used to define onset of sleep. Other laboratories emphasize the appearance of delta slow waves to be more representative of sleep onset during the initial portion of stage N2 sleep (Marzano et al., 2013), although even in these instances there appears to be two different types of slow waves based on their rate of occurrence, amplitude, and scalp distribution (Siclari, LaRocque, Bernardi, Postle, & Tononi, 2014).

Hori, Hayashi, and Morikawa (1994) developed a 5-point scoring system based on characteristic EEG patterns appearing at sleep onset. According to this system, the standard sleep stage N1 is divided into three EEG stages II, III, and IV. The waking state is classified as EEG stage I while the standard stage N2 sleep is classified as EEG stage V. They found that the hypnagogic dream-like state, the period immediately prior to sleep, likely started a few minutes prior to the start of stage N1 and continued for a few minutes past the start of stage N2. Tanaka, Hayashi, and Hori (1996) further extended this by examining changes in hypnagogic EEG by using a 9-point EEG stage classification system. They observed that each EEG stage lasted on average approximately 30 s to 2 min. A difficulty with the use of these detailed classification systems is that the duration of each sub-stage is often too brief to reliably examine responses to external stimuli within each sub-stage. Colrain, Di Parsia, et al. (2000), Colrain, Webster, et al. (2000) and Gora, Colrain, and Trinder (1999) subdivided stage N1 into early and late sub-stages based on the proportion of alpha and theta activity. These studies showed differential brain responses to external stimuli based on whether the EEG within stage N1 was dominated by alpha or theta activity.

1.1. ERPs

A major difficulty encountered in the study of information processing during sleep is that the experimenter does not have direct access to the sleeper's mental state. For instance, the sleeping subject is usually unable to provide either a verbal or behavioural response to external stimuli or queries. Thus, even if they were conscious of the external environment, they may be unable to signal this to the experimenter. The absence of an overt response cannot be used as evidence of the absence of conscious awareness of the stimulus. It is of course possible to awaken the subject and ask them to recall their mental activity. The reliability of such subjective recall is questionable. A failure to recall events immediately prior to awakening may reflect a failure of memory storage or retrieval rather than a lack of awareness of the external stimulus.

Event-related potentials (ERPs) provide an exquisite method to examine the extent of information processing during the transition into sleep during which the subject may no longer signal awareness of an external stimulus (for reviews, see Campbell, Bell, & Bastien, 1992; Dykstra, Cariani, & Gutschalk, 2017; Koch et al., 2016). During wakefulness, all auditory stimuli elicit an obligatory negativity at about 100 ms, ("N1") followed by a positivity at about 200 ms ("P2"). The obligatory N1 and P2 deflections are mainly affected by the physical properties of the stimulus and are especially large to loud and infrequently presented auditory stimuli.

Many studies employ a so-called auditory oddball paradigm to study acoustic change. The subject is presented with a rapid repetition and frequently occurring homogenous "standard" stimulus. At rare (or "odd") times, a feature is changed to form a "deviant" stimulus. The subject is often asked to ignore the auditory sequence of stimuli while attending to another, typically visual, task. The auditory ERPs are thus elicited passively, independent of attention. Such processing is thus said to be pre-attentive, or pre-conscious. The presentation of the standard elicits the obligatory N1-P2. The deviant stimulus also elicits an obligatory N1-P2, but in addition, another later negativity, the mismatch negativity (MMN), signalling the detection of acoustic change (Näätänen, 1990, 1992).

The MMN occurs at about 100–200 ms following stimulus onset and is largest over frontal areas of the scalp, inverting in polarity at the mastoids. In the classic Näätänen (1990, 1992), the MMN is associated with a pre-conscious memory-based comparison system in which the features of the incoming stimulus are compared against the features of the preceding stimuli (the standard) stored in sensory memory. Following presentation of another standard, the sensory memory is improved. However, when a deviant is presented, one of its features fail to match those stored in sensory memory and change is detected. A more recent model maintains that the MMN is elicited by a mismatch between the current auditory input and the predictions formed on the basis of the trends or rules that are automatically detected in recent auditory stimulation (Näätänen, Kujala, & Winkler, 2011; Paavilainen, 2013; Winkler, 2007; Winkler, Denham, & Nelken, 2009), the repeating, homogenous standard thus being a special case of an acoustic pattern. The output

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