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Brain responses to 40-Hz binaural beat and effects on emotion and memory

Nantawachara Jirakittayakorn, Yodchanan Wongsawat*

Department of Biomedical Engineering, Faculty of Engineering, Mahidol University, Salaya, Nakhorn Pathom 73170, Thailand

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ABSTRACT

Gamma oscillation plays a role in binding process or sensory integration, a process by which several brain areas beside primary cortex are activated for higher perception of the received stimulus. Beta oscillation is also involved in interpreting received stimulus and occurs following gamma oscillation, and this process is known as gamma-to-beta transition, a process for neglecting unnecessary stimuli in surrounding environment. Gamma oscillation also associates with cognitive functions, memory and emotion. Therefore, modulation of the brain activity can lead to manipulation of cognitive functions. The stimulus used in this study was 40-Hz binaural beat because binaural beat induces frequency following response. This study aimed to investigate the neural oscillation responding to the 40-Hz binaural beat and to evaluate working memory function and emotional states after listening to that stimulus. Two experiments were developed based on the study aims. In the first experiment, electroencephalograms were recorded while participants listened to the stimulus for 30 min. The results suggested that frontal, temporal, and central regions were activated within 15 min. In the second experiment, word list recall task was conducted before and after listening to the stimulus for 20 min. The results showed that, after listening, the recalled words were increase in the working memory portion of the list. Brunel Mood Scale, a questionnaire to evaluate emotional states, revealed changes in emotional states after listening to the stimulus. The emotional results suggested that these changes were consistent with the induced neural oscillations.

1. Introduction

Gamma oscillation is neural oscillation that maintain long-range communication in the brain (Fries, 2005) including the communication between thalamus and cerebral cortex, and within cerebral cortices themselves (Llinas et al., 2002). Thalamus and cerebral cortex, normally, communicate via thalamocortical circuit including 2 types of thalamic neurons which are thalamic core neurons, and thalamic matrix cells. The former sends projection fibers to specific cortical areas, i.e., primary auditory cortex while the later send projection fibers to widespread cortical areas, i.e., other auditory areas. These connections including connections within cerebral cortices communicate to one another by synchronization of neural activities which oscillate at the same frequency (Jones, 2009). The occurred oscillation which is generated for schema sending is gamma oscillation (Llinas and Ribary, 1993).

Gamma oscillation is associated with arousal maintenance of the brain during waking state (Vanderwolf, 2000; Gray, 1999; Gray and Singer, 1989; Llinas and Pare, 1991). It is found during consciousness and the oscillation pattern is interrupted when lack of consciousness occurs. These are clearly observed in rats. During normal postures, which are head held up against gravity, and eyes open, gamma oscillation pattern was found. After the rats were treated with some medicine to let them in stupor, gamma oscillation pattern was disrupted by suppression. However, the experiment indicated that slow wave oscillation was generated in the rats' brain when they were immobile in waking state. This slow wave is explained as similar to alpha oscillation in humans. Therefore, it is related to consciousness during waking state.

In addition to association to arousal and consciousness, gamma oscillation also plays an important role in sensory integration process (Ross and Fujioka, 2016; Llinas and Ribary, 1993; Mima et al., 2000; Pantev et al., 1991; Tallon-Baudry et al., 1996; Bertrand and Tallon-Baudry, 2000). When a stimulus is received by receptors and transduced into signal sending to the brain – primary area of the brain related to the signal is active to process the signal. This mechanism leads to sense that stimulus. However, to perceive higher perception or to process more detail of the stimulus, other brain areas related to the primary area must co-operate during the process (Fries, 2005; Ross and Fujioka, 2016; Gray et al., 1989). For example; after auditory information is received, primary auditory cortex analyzes that auditory stimulus (Harris et al., 2009). Other auditory features such as the meaning of that stimulus are required other brain areas to process (Harris et al., 2009; Vermeire et al., 2016). The process that integrates, groups, and analyzes the received information is called binding process

* Corresponding author at: Brain Computer Interface Laboratory (BCI Lab), Faculty of Engineering, Mahidol University, Nakhorn Pathom 73170, Thailand.
E-mail addresses: Nantawachara.jir@student.mahidol.ac.th (N. Jirakittayakorn), Yodchanan.won@mahidol.ac.th (Y. Wongsawat).

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or sensory integration. One piece of evidence supporting binding process is aging. Elderly are frequently found to be able to hear sound but unable to understand what has been heard (Martin and Jerger, 2005). This occurs because binding process is impaired in elderly (Ross and Fujioka, 2016; Vermeire et al., 2016). Binding process occurs by co-operation among several brain areas via connections between thalamus and cerebral cortex, and within cerebral cortices, themselves; therefore, that co-operation is synchronization among those brain areas. The mentioned synchronization is neural synchronization which corresponds to gamma oscillation. Therefore, gamma oscillation is an important mechanism underlying the binding process.

Another interested point is that gamma oscillation plays an important underlying role in cognitive functions (Fries, 2009; Fries et al., 2007; Ward, 2003; Jensen et al., 2007; Herrmann et al., 2004). By which attention level of an individual increases while gazing on an object, gamma oscillation also increases. However, when visual field of attention is shifted to the other side, gamma oscillation evokes in contralateral hemisphere (Ward et al., 2006). Another piece of evidence is gazing at a moving bar (Muller et al., 1996). In the previous study, there were 2 types of moving bars; the first type was one long bar moving in one direction, and the other type was two short bars moving in opposite direction. The first case, long bar, induced gamma oscillation in humans while the second case, 2 short bars, did not induce gamma oscillation. The results of both attention and moving bar support sensory integration or binding process. When attention level increases, several brain areas have to function to analyze higher perception of the stimulus. In addition, gazing at long moving bar requires 2 eyes coordinating together and leading to binding process while gazing at 2 short moving bars does not require coordination. A previous study claimed that gamma oscillation and memory process associates and links to each other (Tallon-Baudry et al., 1998). In that experiment, visual task was conducted in participants; when the same previous object was presented, gamma oscillation was observed in the brain at frontal sites. Moreover, prefrontal cortex is an important role in emotional responses beside amygdala, hippocampus, and anterior cingulate. Changes in emotional states induce gamma oscillation in prefrontal part of the brain (Damasio, 1995; Davidson, 1992; Davidson et al., 1990; Derryberry and Tucker, 1992; Davidson and Hugdahl, 1995). It can be clearly seen that gamma oscillation associates with cognition process.

Cognition is the mental action or process of acquiring knowledge and understanding through thought, experience, and the senses defined by oxford dictionary (English Oxford Living Dictionaries, n.d.). It includes several processes and mechanisms; for example, attention, memory and working memory, judgment and evaluation, reasoning and computation, problem solving and decision making, comprehension and language, and perception. Cognition in humans occurs both during consciousness and unconsciousness. Cognition, normally, can be changed along lifetime by surrounding environment, and new knowledge is also developed by existing knowledge; however, this concept seems to be abstract. Enormous studies have shown that gamma oscillation has been linked with cognition regarding several processes as mentioned.

The mentioned gamma oscillation is referred to 40-Hz oscillation (Nadasdy, 2010; Fries, 2009; Ross and Fujioka, 2016; John, 2002; Plourde et al., 1998). Gamma oscillation is generally displayed in frequency range of 30 to 100 Hz; however, 40-Hz is typically considered as gamma oscillation. This oscillation, 40-Hz, is generated by neural synchronization according to existing evidences. Firstly, 40-Hz auditory steady-state response (ASSR) expresses similar characteristics to fast-spiking interneurons which are hypothesized as main source of gamma oscillation (Vierling-Claassen et al., 2010). Secondly, combination of sensory inputs indicates inconsistencies with temporal dynamics of 40-Hz ASSR onset transition (Ross et al., 2002). This leads to another additional gamma oscillation components. Lastly, changing of stimulus feature or changing of stimulus resets 40-Hz oscillation (Ross, 2008; Ross and Pantev, 2004; Ross et al., 2005), as explained by the binding process. These findings support that 40-Hz oscillation represents gamma oscillation of interest based on several aspects mentioned previously: long-range communication of the brain, sensory integration or binding process, and cognitive related functions.

Another interesting issue of gamma oscillation is the change from gamma oscillation to beta oscillation which appears after a sufficiently high stimulus intensity is received (Traub et al., 1999; Haenschel et al., 2000). This changing phenomenon is called gamma-to-beta transition. As a stimulus is received into the brain, gamma oscillation occurs in response to that stimulus; if the intensity of the stimulus is high enough, the beta oscillation subsequently appears as a salient activity. Gamma oscillation is normally generated in primary sensory cortex in response to the stimulus and other specific association areas (Barth and MacDonald, 1996; Pantev et al., 1991; Pantev, 1995); however, occurred beta oscillation induced by the stimulus is generated in association areas and widespread areas across the cerebral cortex (Roelfsema et al., 1997; von Stein et al., 1999). In addition, prefrontal cortices also express the beta oscillation (Giard et al., 1994; Loveless et al., 1996; Lu et al., 1992). This gamma-to-beta transition is seemingly explained as sensory gating (Clementz et al., 2002; Crawford et al., 2002; Hong et al., 2004) which is neural process to filter out unnecessary stimuli in the brain from several stimuli in surrounding environment and is likely described as attention switching (Whittington et al., 1997) which is one of makers showing that individuals focus their attention on the stimulus. A previous study reported (Kisley and Cornwell, 2006) that increase beta oscillation in gamma-to-beta transition process is simultaneously observed with increase gamma oscillation in cases of high enough stimulus intensity.

Beta oscillation is one of neural oscillations in addition to gamma oscillation. It represents activity in range of 12 to 30 Hz. Beta oscillation is normally observed during normal waking state with consciousness and also corresponds to the brain activity in that brain area (Clementz and Blumenfeld, 2001; Karakas and Basar, 1998). For example, beta oscillation over motor cortex are associated with muscle contraction and over prefrontal cortex reflects focus or selective attention, thinking process, and problem solving. Beta oscillation is also a marker of gamma-to-beta transition process to illustrate selective attention to the stimulus in sensory gating. It is known that beta oscillation can be split into 3 groups according to frequency: beta1 (12–15 Hz), beta2 (15–18 Hz), and beta3 (18–25 Hz.) oscillations. However, the 25–30 Hz frequency range is also classified as beta oscillation but known as high beta activity. Different ranges of beta oscillation indicate different intensities of brain activity.

Due to the functions of the brain mentioned above, the brain expresses its characteristics oscillation activities depending on its functions or behavioral states. Each behavioral state contributes to specific brain characteristic which induces the brain to response. However, counter process of the responses is also interesting and can be investigated by inducing the brain to display some specific characteristic and, consequently, letting the brain to perform its function. Investigations on the counter process are lacking; therefore, studying of the brain function after inducing, counter process, is needed. This study aims to investigate the brain responses to stimulus and its function during cognitive function, especially memory, utilizing a stimulus to induce some brain characteristics which are gamma and beta oscillations. These 2 oscillations relate to sensory binding, brain function in response to stimuli, attention, and memory. Hypothesizes of this study are as follows: 1) the brain can be induced by the stimulus and displays some specific characters which are gamma and beta oscillations; and 2) cognitive function, especially working memory, is changed after the brain is induced by the stimulus.

The stimulus used in this study is auditory stimulus which is binaural beat. Binaural beat is a beat phenomenon occurring in the brain upon receiving of 2 pure tones that are almost the same in terms of amplitude and intensity but with slightly different frequencies, separately each ear at the same time. The beat is generated at the superior