A mathematical model to mimic the shape of event related desynchronization/synchronization

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ABSTRACT

Rhythmic oscillatory activities of the sensory cortex have been observed after a presentation of a stimulus. This activity first drops dramatically and then increases considerably that are respectively named event-related desynchronization (ERD) and event-related synchronization (ERS). There are several effective factors that can alter the ERD and ERS pattern. In this study, a mathematical model was presented that produced ERD and ERS pattern in response to a stimulus. This model works based on the synchronization concepts. The proposed model provided different suggestions about the reason behind the relationship between the encoding of incoming sensory information and the oscillatory activities, effective factors on the characteristics of neuronal units, and how may these factors affect the amplitude and latency of the ERD and ERS.

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1. Introduction

Response to an incoming event or stimulus is one of the basic tasks of the nervous system in living organisms. In all neurocognitive experiments, this response and its characteristics were studied to find more about the features of neural systems. It has been shown that the sensory cortex has oscillatory activities in different frequency bands in response to a stimulus. Until now, the relationship between these rhythmic activities and encoding the incoming stimulus has not been clearly understood (Mazzoni et al., 2008). Another characteristic of neuronal systems’ response to an incoming event is a drop of their activities that has been termed ERD and then an increase in their ongoing oscillations that is called ERS (Lemm et al., 2009). Both ERD and ERS may be affected by different features of the ongoing task. Gamma band ERS was observed just before the onset of a movement. Beta-rhythm ERD was observed during movement execution (Grabska-Barwińska and Zygierewicz, 2006). Alpha-rhythm ERD was seen in perceptual, judgment and memory tasks (Guger et al., 2005).

Based on the results of the previous studies, ERD characteristics depend on several factors, including the condition of eyes (open or close) in the presence of visual stimuli (Woertz et al., 2004), the value of the prestimulus reference power (Arieli et al., 1996; Woertz et al., 2004), the partial pressure of oxygen (Guger et al., 2005), task complexity (Boiten et al., 1992), attentional demand (Ohara et al., 2004), depth of anesthesia (Kisley and Gerstein, 1999), and the experimenter’s instruction (Boiten et al., 1992).

Fast decreasing of the partial pressure of oxygen can increase the cortical excitability level and consequently, may lead to the decrease of post-reaction Beta-rhythm ERS (Guger et al., 2005).

It was reported that the ERD amplitude and the latencies of ERD and ERS were larger when eyes were open in comparison with closed eyes in the presence of a light stimulation (Woertz et al., 2004). When the eye is open, the intensity of the light reaches to the brain is higher than when eyes are closed. On the other hand, the cognitive condition is also different in open and closed eyes. The drowsy state is more probable in the closed eye condition. A positive correlation between the prestimulus reference power value, ERD size, and cognitive performance was reported in previous studies (Doppelmayr et al., 1998; Woertz et al., 2004). Large and low reference power respectively correlates with a low and large extent of Alpha- and Theta-rhythm ERD. Reference power has no correlation with Delta-rhythm ERD/ERS (Doppelmayr et al., 1998). Stimuli with high intensity induce larger mu- and Beta-rhythm ERD/ERS than that of with low intensity (Stancák et al., 2003). It was shown that the repetition of a stimulation led to the exponential decrease of ERD/ERS (Stancák et al., 2003).

It was reported that the experimenter instruction to perform as fast as possible, can affect the size of ERD (Boiten et al., 1992). The duration of relative ERD can increase by the increment of the task complexity or the attention level (Boiten et al., 1992). The pres-
stimulus Alpha- and mu-rhythm levels affect the evoked responses (Nikouline et al., 2000).

Attention decreases the first LFP’s negative amplitude and increases the first LFP’s positive amplitude. In both positive and negative LFP, attention reduces their latency. Elevation of the stimulus contrast leads to the decrement of response latency and increment of positive and negative response amplitude (Sundberg et al., 2012). Presentation of a non-frequent stimulus can change the LFP’s positive and negative deflection amplitude and latencies (Nieto-Diego and Malmierca, 2016).

In summary, the observation of ERD and ERS in response to a stimulus has been reported in lots of studies. Several effective factors were also reported. However, the basis of the appearance of ERD and ERS remains mainly unknown.

In this study, we proposed an oscillatory model that showed ERD and ERS pattern in response to a stimulus. Using the proposed model, the impact of some factors relates to the nature of stimuli and the neural system on ERD and ERS features can be investigated. Results may also help to suggest a reason for the appearance of sensory cortex oscillatory activities to encode an incoming sensory information.

2. Model

Since synchronization is usually defined for oscillatory outputs, modeling of ERD or ERS requires the definition of some oscillators. In our proposed model, we selected Van der Pole oscillator (Eq. (1)) to represent a pool of oscillatory neurons. The Van der Pole oscillator was considered as a global model of neurons, regardless of neuronal details and chemical reactions (Nomura et al., 1993).

\[
\begin{align*}
\dot{X} &= (\lambda - Y^2)X - p^2Y \\
\dot{Y} &= X
\end{align*}
\] (1)

In Eq. (1), X and Y determine the state variable and the output of the oscillator (pool of neurons), respectively. When the value of \( \lambda \) is lower than zero (\( \lambda < 0 \)), there is no oscillation, and when it is higher than zero and lower than one (\( 0 < \lambda < 1 \)), the unit can oscillate at frequency and amplitude that are respectively determined by the value of p and \( 2/\sqrt{\lambda} \) (Balanov et al., 2008) (Fig. 1).

The Van der Pole oscillator introduced in Eq. (1) has no input. It is a self-oscillator. In our study, the Van der Pol oscillator was considered as a representation of a pool of neurons that responded to an incoming event. This event can be an auditory, visual, tactile or another kind of stimulus that has been coded in some regions of peripheral or central nervous system. This coded stimulus can affect another neural population through the way mentioned in Eq. (2).

\[
\begin{align*}
\dot{X} &= (\lambda - Y^2)X - p^2Y + \text{Stimulus} \\
\dot{Y} &= X
\end{align*}
\] (2)

In the current study, the stimulus has been represented by a sine wave (Eq. (3)). The amplitude of the sine wave, \( A_s \), is associated with the strength of the stimulus (event) and its frequency, \( \omega_s \), is a representation of stimulus features. This assumption is supported by evidence of rate or frequency coding of information in the brain (Kumar et al., 2010; Onken et al., 2014). It should be noted that to code all features of a stimulus, it is required to simulate it with a series of sine waves with different frequencies that each of them represents and codes one specific feature of the stimulus. However, to avoid the complexity of the model and without loss of the entirety of the problem, we have assumed that there is a predominant frequency in this frequency spectrum that can be considered as the representation of each stimulus. However, in Section 4.1, the simulations of the model are presented for more complex stimuli.

\[
\text{Stimulus} = Y_s(t) = A_s \sin(o_\text{stim}t)
\] (3)

Fig. 1. The output of Van der Pole oscillator with the different value of \( \lambda \) and p. The graphs in the left column show the output of the oscillator in the time domain, and the graphs in the right column show the behavior of the oscillator in the state space. First row: \( \lambda \) is lower than zero, the system attracts to its stable \((X=0, Y=0)\) fixed point; second row: \( \lambda = 0.2 \) is higher than zero. The system oscillates with a frequency determined by p; third raw: the increment of p from 1 to 2 increases the frequency of oscillations.

Fig. 2. A schematic of the proposed model and its elements.

Fig. 2 shows a simple schematic of our proposed model and its elements.

According to Fig. 2, an event is coded by \( Y_s \), which is an oscillatory wave (i.e., sine wave). Then, the coded stimulus tries to be synchronized with specified units in a higher level of processing stage for further processing. In the nervous system, each stimulus is further processed by neural populations that their receptive fields are specified to features of that stimulus Fritz et al., 2007). In our proposed model, this receptive field is determined by the frequency of the neuronal ensemble. That is, neurons that their frequency of oscillation is close to the frequency of the coded stimulus responds to it more than other neurons (Fritz et al., 2007). We have considered two units of neurons (Eqs. (4) and (5)) each of which oscillates with a specified frequency (i.e., \( p_1 \) and \( p_2 \) in Eqs. (4) and (5)). Therefore, it has been expected that the unit that its frequency of oscillation is close to \( \omega_s \) responds to the stimulus.
(Eq. (3)) more than the other unit.

neuronal unit 1 \( \begin{align*} \dot{X}_1 &= (\lambda_1 - Y_1^2)X_1 - p_1Y_1 + B_1 \times A_S \sin(\omega_S t) \\ Y_1 &= X_1 \end{align*} \) \( \text{(4)} \)

neuronal unit 2 \( \begin{align*} \dot{X}_2 &= (\lambda_2 - Y_2^2)X_2 - p_2Y_2 + B_2 \times A_S \sin(\omega_S t) \\ Y_2 &= X_2 \end{align*} \) \( \text{(5)} \)

In Eqs. (4) and (5), \( B_1 \) and \( B_2 \) are coupling weights between the incoming oscillatory input and neuronal units. The higher value of \( B_1 \times A_S \) (i = 1 and 2) leads to the higher probability of the response of neuronal units to the incoming input. Eqs. (4) and (5) are forced Van der Pol oscillator. In these equations, the stimulus (i.e., the sine wave) is master and the neuronal unit with the self-oscillator Van der Pol equation (Eq. (1)) is the slave. In an appropriate value of \( B_1 \times A_S \) (i = 1 and 2), the slave oscillator synchronizes with the master oscillator.

The shaded area in Fig. 3 demonstrates values of \( K = B \times A_S \) that can lead to the synchronization. As shown in Fig. 3, these values also depend on the master frequency value (\( \omega_S \)) and also to the amplitude of the master oscillator. If the value of \( K \) is lower than the amplitude of the slave, the border of the synchronization cannot obtain from the Eq. (6). This border has been shown by a solid line in Fig. 3. When the mentioned condition is not satisfied, the border can be calculated from Eq. (7), which has been demonstrated by a dotted line in Fig. 3.

\[
K \geq 4\sqrt{\lambda_1\omega_S}|\Delta| \\
\Delta = \frac{p^2-\omega_S^2}{2\lambda_1} \approx p - \omega_S \\
K \geq \sqrt{2\lambda_1}\left|p^2 - \omega_S^2\right| 
\]

The assumption of forced synchronization between the coded stimulus (i.e., the sine wave) and the activity of neuronal units is based on the results reported in previous studies. For example, in vision, the stimulus is coded by retina’s cells, and the coded stimulus is sent to the thalamus and primary visional cortex for further processes. The pathway between the retina and the higher level visual processors is demonstrated by a unidirectional arrow (Cruz-Martín et al., 2014; Diederich et al., 2014; Urbaniski et al., 2014), which can be interpreted as a master-slave relationship (forced synchronization). However, neuronal units in the primary sensory cortex interact with each other mutually (Carandini et al., 1998) that needs to be modeled by a mutual synchronization, which is used in the extended version of the model in Section 4.2.

The results of the numerical simulation of the proposed model with different values of the effective parameters are reported in the next section.

3. Simulation results

In this section, the effect of different parameters on ERD and ERS are investigated. Fig. 4 shows the push of the response of two units of the model (i.e., Eqs. (4) and (5)) to a stimulus that starts from the time-sample 20 and lasts into the time-sample 90. Other parameters of the model were set on \( \lambda_{1,2} = 0.2, B_{1,2} = 1, A_S = 1, p_1 = 6, p_2 = 8, \) and \( \omega_S = 6 \). Therefore, unit one that its intrinsic frequency is close to the frequency of the stimulation starts to be synchronized with it.

As shown in Fig. 4, the push of the activity of unit 2 did not change considerably. However, the push of the activity of unit 1 had a significant decrease and after a while started to increase, considerably. The first decrease, which is called ERD, is due to the time required for the phase alignment of two oscillators (i.e., unit 1 and the stimulus). After a while, the phase of the two oscillators gradually becomes similar with each other. Then, as a result of the synchronization between two oscillators, the activation of unit 1 begins to increase, which is named ERS. Fig. 5 shows the frequency spectrum of the oscillators’ activities (i.e., unit 1, unit 2, and the stimulus) during both ERD and ERS intervals.

Fig. 5 shows an increase of the activity of unit 1 after the synchronization with the coded stimulus. This increment was considered as a response of unit 1 to the stimulation. However, unit 2 could not synchronize with the coded stimulus and consequently, did not respond to it. Fig. 6 demonstrates units’ response to a shorter stimulus.

The pattern of the activity of unit 1 was approximately similar to the neural activities that were recorded from different layers of the brain in response to a stimulus. For instance, some of them were shown in Fig. 7.

As mentioned before, ERD period is the time required for the alignment of the phase of neuronal unit response with the coded stimulus. The initial phase difference between two oscillators de-
Fig. 5. Frequency spectrum of the response of units to a stimulus that its frequency is close to the intrinsic frequency of unit one (\(\lambda_1, \lambda_2 = 0.2, B_1, B_2 = 1, A_5 = 1, p_1 = 6, p_2 = 8, \text{and } a_5 = 6\)): (a) during ERD interval; (b) during ERS interval; The stimulus duration is from sample time 20 to 90.

depends on the initial condition. Fig. 8 shows the effect of the initial condition on ERD and ERS patterns.

According to Fig. 8, increasing the initial activities before the stimulus presentation increases the delay of synchronization. That is, ERS period appears with more delay.

The other factor that can affect the ERD and ERS delay and amplitude is the multiplication of the stimulus strength and the coupling weight \((K = B \times A_5)\). The effect of this factor on the simulation results was shown in Fig. 9.

As shown in Fig. 9, model demonstrates that increasing the stimulus intensity leads to the increment of ERD and ERS amplitude and also to the decrement of the ERD latency.

Fig. 10 shows the effect of the units’ oscillation amplitude (i.e., the value of \(\lambda\)) on the pattern of units’ responses.

According to Fig. 10, increasing the value of the units’ oscillation amplitude from 0.1 to 0.3 increases the ERS amplitude, but has no significant effect on the ERD amplitude and latency. However, a more increment from 0.3 to 0.4, considerably affect the ERD pattern.

4. Further extension of the proposed model

In order to keep the model simple and analytically trackable, some of the facts in the neuronal behaviors and their interactions were ignored in topics discussed in previous paragraphs. However, the proposed model has the capability to be developed for entering some of these facts such as dealing with more complex stimuli and the interaction between two receiving oscillatory units. In the following sections, the simulation of the model in the new conditions are presented.

4.1. Dealing with more complex stimuli

In previous simulations, the input stimulus was represented as a single-frequency sine wave. A relationship between the frequency characteristics of neuronal activities and the features of an input stimulus were reported in previous studies. Therefore, if
we consider a more complex stimulus with different features, the stimulus can be represented by a wave with different frequencies. Fig. 11 shows the results of the proposed model simulation by different input stimuli presented in Eqs. (8)–(11).

Stimulus = \( Y(t) = A_1 \sin(\omega_1 t) \)
\( A_1 = 1, \ \omega_1 = p_1 = 6 \)  \hspace{1cm} (8)

Stimulus = \( Y(t) = A_1 \sin(\omega_1 t) + A_2 \sin(\omega_2 t) + A_3 \sin(\omega_3 t) \)
\( A_1 = A_2 = A_3 = 1, \ \omega_1 = p_1 = 6, \ \omega_2 = 10, \ \omega_3 = 13 \)  \hspace{1cm} (9)

Stimulus = \( Y(t) = A_1 \sin(\omega_1 t) + A_2 \sin(\omega_2 t) + A_3 \sin(\omega_3 t) \)
\( A_1 = A_2 = A_3 = 1, \ \omega_1 = p_1 = 6, \ \omega_2 = p_2 = 8, \ \omega_3 = 13 \)  \hspace{1cm} (10)

Stimulus = \( Y(t) = A_1 \sin(\omega_1 t) + A_2 \sin(\omega_2 t) + A_3 \sin(\omega_3 t) \)
\( A_1 = A_3 = 1, \ A_2 = 0.2, \ \omega_1 = p_1 = 6, \ \omega_2 = p_2 = 8, \ \omega_3 = 13 \)  \hspace{1cm} (11)

The stimulus presented by Eq. (8) is the same as the scenario tested in previous sections, which the frequency of the input stimulus is consistent with the frequency of unit 1 oscillations. In Eq. (9), the stimulus includes three features that each of them represented by a frequency. One of the features was coded by \( \omega_1 \) with \( A_1 \) amplitude. The value of \( \omega_1 \) was equal with the frequency of unit 1 oscillations, \( p_1 \). Therefore, as shown in Fig. 11(b), this feature excited unit 1. However, according to the results of simulation shown in Fig. 11(b), the activities of unit 2 also slightly increased compared to the single-frequency input scenario. A possible reason is explained in the Discussion part. It should be noted that, in the current version of the model, there is no unit to respond to other frequencies (i.e., other features), \( \omega_2 \) and \( \omega_3 \). To extend the model to respond to other frequencies, more oscillatory units (i.e., neuronal populations) need to be added to the model. This can be done for future works with a different goal that is mentioned in the Conclusion part. In Eq. (10), the stimulus includes three frequencies (i.e., three features) with equal amplitudes. The first frequency is equal to the frequency of the unit 1 oscillations (i.e., \( \omega_1 = p_1 \)). The second frequency is equal to the frequency of the unit 2 oscillations (i.e., \( \omega_2 = p_2 \)). Therefore, the activities of both units 1 and 2 increased in response to such a stimulus (see Fig. 11(c)). There is no unit to respond to the third frequency (but can be added for future works). However, this frequency interfered with other frequencies and affected the response of both units. The non-smooth push of the activities of both units (in Fig. 11(b-d)) can be due to the interference of different frequencies on each other. This scenario can be the same as considering the entrance

Fig. 8. Effect of the initial condition (IC) on the pattern of units’ response, ERD, and ERS (\( \lambda, 1.2 = 0.2, B, 1.2 = 1, A_S = 1, p_1 = 6, p_2 = 8, \) and \( \omega_3 = 6 \)).

Fig. 9. The effect of increasing the stimulus intensity on the (a) ERD amplitude, (b) ERD latency, and (c) ERS amplitude in the proposed model (response of unit 1): In the equation \( K = B \cdot A_S \), B has been fixed on one, and \( A_S \) has been changed in the x-axis, (\( \lambda, 1.2 = 0.2, B, 1.2 = 1, p_1 = 6, p_2 = 8, \) and \( \omega_3 = 6 \)).

Fig. 10. Effect of increasing the value of the units’ oscillation amplitude (i.e., the value of \( \lambda \)) on the pattern of ERD and ERS (\( B, 1.2 = 1, A_S = 1, p_1 = 6, p_2 = 8, \) and \( \omega_3 = 6 \)).
of two simple stimuli simultaneously: one stimulus (with one feature) is coded by \( \omega_1 \), and the other stimulus (with one feature) is coded by \( \omega_2 \). As shown in Fig. 11(c), the model responds to both frequencies (features or stimuli). In such a situation, the role of top-down processors becomes more important that are described in the Discussion part. The stimulus shown in Eq. (11) is similar to the previous one, with the difference that the amplitude of one of the frequency components is less than the rest \((A_1 = A_3 = 1, A_2 = 0.2)\). This component is related to the frequency of the unit 2 oscillations. As shown in Fig. 11(d), unit 2 did not respond to this component because of its low strength. Therefore, as mentioned before, the strength of the stimulus can also affect the response of neuronal units.

In previous simulations, we did not consider the interaction between receiving units. In the next section, the equations of the model extended to investigate the effect of the coupling between units.

4.2. Interaction between two receiving oscillatory units

The interaction between neuronal populations was reported in different studies (Carandini et al., 1998; Vaadia et al., 1995; Womelsdorf et al., 2007). In the previous simulations, these interactions were ignored in order to simplify the problem. To add such an interaction, two receiving units were coupled. The coupling of two or more Van der Pole units was also used in some other biological and non-biological studies (Balanov et al., 2008; Barrón and Sen, 2009; dos Santos et al., 2004; Leung, 2003; Pastor-Diaz and López-Fraguas, 1995). According to the results of these studies, the mentioned coupling was done by adding a term to the Eqs. (4) and (5). This alternation caused the units to mutually interact with each other. Therefore, the output of unit 1 could affect the activities of unit 2 and vice versa. Eqs. (12) and (13) show the extended model.

neuronal unit (1) → \[
\begin{align*}
X_1 &= (\lambda_1 - Y_1^2)X_1 - p^2Y_1 + B_1 \\
&\quad + A_1\sin(\omega_1 t) + C_{1,2} \times (Y_2 - Y_1) \\
Y_1 &= Y_1
\end{align*}
\]  

neuronal unit (2) → \[
\begin{align*}
X_2 &= (\lambda_2 - Y_2^2)X_2 - p^2Y_2 + B_2 \\
&\quad + A_2\sin(\omega_2 t) + C_{1,2} \times (Y_1 - Y_2) \\
Y_2 &= Y_2
\end{align*}
\]  

where \( C_{1,2} \) represent the coupling weight between units 1 and 2. Results of simulations, which are shown in Fig. 12, show the effect of the strength of the coupling weight on the response of two receiving units to the incoming stimulus.

As shown in Fig. 12, increasing the strength of the coupling weight between two receiving units affects the response of both units in two ways: 1- decreases the desynchronization period, and 2- increases the qualitative and quantitative similarity of the activity of two units. Some possible reasons for these observations are provided in the Discussion part.

5. Discussion

In this paper, a mathematical model was presented to show a possible basis of the appearance of a considerable decrease and then an increase in the activity of neural units recorded from different layers of the brain in response to a stimulus. The proposed model consisted of two oscillators that worked based on the synchronization concepts. Comparing Figs. 6 and 7 shows that the proposed model can mimic the mentioned decrease and then the increase of neural activities after the presentation of a stimulus. In previous studies, the ups and downs of activities of neuronal units were attributed to the chemical activity inside and outside the cells (Buzsáki et al., 2012). The results of simulations suggest that the drop of neural units’ response may also be as results of nonalignment the unit’s response with the coded event or stimulus (i.e., ERD). After a while, the phase of the unit’s response is synchronized with the phase of the oscillation of the coded event or stimulation (i.e., ERS). The amplitude of the responsive neuronal oscillator increases as a result of this synchronization. This observation suggests a possible reason for the observation of sensory
cortex rhythmic activity in response to an incoming sensory information.

Simulations demonstrate that the amplitude and latency of ERD and ERS depend on different factors. One of these factors is the multiplication of the input strength and the coupling weight. As shown in Fig. 9, simulation results demonstrate the effect of the input intensity on the amplitude and latency of ERD and ERS, which are approximately consistent with a real experiment records in Stancák et al. (2003). According to simulation results, it can be suggested that increasing the input strength facilitates the procedure of the forced synchronization. Therefore, the latency of ERD decreases and the synchronization between the master and slave oscillators occurs sooner with higher amplitude. Based on the model equations, the coupling weight between the master and slave oscillators can have the same effect as the input strength. Physically, this coupling weight can be interpreted as the weight or the attention attributed to the input stimulus. Thus, the proposed model suggests that increasing the attention to a stimulus can also accelerate the synchronization.

Another effective factor is the primary amplitude of the slave oscillator (i.e., units 1 or 2 that respond to stimuli). The increment of this factor, to a certain extent, had no effect on the latency and the amplitude of ERD but increases the amplitude of ERS. This result was consistent with the observations that were reported in Boiten et al. (1992). However, the simulation results revealed that a more increment of the primary amplitude of the responsive neuronal units had a considerable effect on the ERD pattern. According to the explanation provided in the Model part, increasing the amplitude of the responsive neuronal units (λ) affects the frequency of responses and consequently, changes the procedure of synchronization.

The procedure of the phase synchronization also depended on the initial condition that was shown in Fig. 8. These results provide a possible justification for the changes of neuronal response to deviant events or stimuli. A deviant stimulus is an event that is different from its previous stimuli at least in one feature. A considerable increase has been reported for the drop in the neuronal activity after a deviant stimulation (Nieto-Diego and Malmierca, 2016). After some similar stimuli, the condition of responsive neural activities is so that is ready to respond to another similar event. Therefore, the initial condition is not appropriate to respond to a deviant stimulus, and consequently, may affect the ERD pattern and decelerates the procedure of synchronization.

In the extended simulations with a more complex stimulus, shown in Fig. 11(b), the activities of unit 2 slightly increased compared to the simple (single-frequency) stimulus. The push of the activities of both units (in Fig. 11(b-d)) was not as smooth as the simulation with a simple (single-frequency) stimulus (shown in Fig. 11(a)). Mathematically, these observations can be due to the interference of different frequencies on each other. In psychophysical experiments, a similar effect was also reported. That is, some features of a stimulus had slight effects on neuronal populations that were sensitive to other features. For instance, neuronal populations that are sensitive to the auditory features such as colors, or vice versa (Chiou et al., 2013).

According to the results shown in Fig. 11(c), the stimulus can simultaneously excite both receiving units of the model if it consists of frequencies that are consistent with the frequencies of units 1 and 2 oscillations. Two scenarios can be considered for this observation: (1)- simultaneous excitation of both units can be attributed to the response of units to two features of a complex stimulus (e.g., color and shape in a visual stimulus); (2)- simultaneous excitation of both units may represent the response of the neuronal system to two simple stimuli that are presented simultaneously. For both scenarios, the model can be extended for future works by considering the role of top-down processors. In the first scenario, some higher-level processes are required to combine different features to provide a complete understanding of the presented stimulus, which is known as “feature integration” (Treisman and Gelade, 1980). In the next scenario, if one of the simple stimuli is the target and the other is a distraction, the excitation of the unit responds to the distraction needs to be inhibited by top-down processors (Theeuwes et al., 2000).
As shown in Fig. 12, considering a coupling weight between two receiving units affects the results of simulations. In lower values of the coupling weight, the connection between two units is weak and the result in the synchronization interval is nearly the same as when there is no connection between two units (see Fig. 12(a) and (b)). However, increasing the strength of the coupling weight had considerable effects on the activities of receiving units in the synchronization interval. According to the Fig. 12(c) and (d), the increase in coupling between the two units leads to the increment of the similarity between the activity of two units. Mathematically, this result is due to the high value of coupling weight that can lead to a strong mutual synchronization between two units. As mentioned before, in the procedure of the forced synchronization between each receiving unit and the coded stimulus, a desynchronization interval (ERD) is observed before the ERS. Several factors were introduced that affected the ERD size and duration. Results demonstrated in Fig. 12 show that the value of the coupling weight between two receiving units can also be considered as another effective factor on ERD characteristics. The mutual synchronization between two units forces them to act similarly, which may lead to the decrease of the ERD interval.

6. Conclusion

The mathematical model proposed in this paper mimics the shape of ERD and ERS of neuronal units in response to a stimulus. This model provides different suggestions about the reason behind the observed effect of different factors on the pattern of ERD and ERS. For future work, the response of the model to a series of stimulus would be investigated. This extension needs to define a function for changes of the coupling weight or the attributed attention to one stimulus to another incoming event. In the current version of the model, the primary amplitude of slave oscillators (i.e., responsive neuronal units) has been fixed. However, the increment of ERS amplitude to a deviant stimulus shows that the mentioned amplitude may be variable.

If the goal is the study of the response of neuronal units to different features of a stimulus, the model should be extended by adding several oscillatory units that each of them responds to one feature. The model can also be developed by considering the role of higher-level processors for feature integration or the inhibition of the distraction effects.

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Declaration of interest

There is no declaration of interest.

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