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Alpha and Theta Rhythms as Markers of Cognitive Effort

Natalia A. Zhozhikashvili[1]✉, **Anna D. Bakumova**[2]
[1] National Research University Higher School of Economics
[2] Psychological Institute of the Russian Academy of Education
✉ nzhozhik@gmail.com

Annotation: **Introduction.** This review article combines the theory of motivational intensity and the theory of mental effort with studies of oscillatory correlates of the performance of complex cognitive tasks. The phenomenon of effort has been a longstanding subject of research in fundamental psychology. Theories describing the cognitive mechanisms of mental effort have been developed in recent years. However, further research is needed to explain the mechanism of effort modulation during task performance. **Theoretical justification.** Mental effort can be defined as an active volitional process of mobilizing resources to maintain a particular behavior. The theory of motivational intensity, in conjunction with theories of mental effort, describes the cognitive and motivational factors that modulate the effort invested in the performance of a task. Interpreting the oscillatory correlates of individual cognitive processes in the context of effort theories may allow one to develop an understanding of the mechanism underlying the distribution and modulation of mental effort. The purpose of this paper is to review the existing experimental data on the modulation of task-related oscillations and compare the research results with the predictions of force theories. **Results.** The article reviews research on the power of oscillations as correlates of various controlled processes required by a cognitive task. The severity of the oscillatory effects associated with the performance of the task increases with the complication of the task and with increased motivation to perform. When performing particularly complex tasks, there are individual differences in indicators of brain activity, which, apparently, can only be explained through the motivational-emotional reaction of the subject to complexity. **Discussion of the results.** The effects found as a result of the literature review are consistent with the predictions of the theory of motivational intensity about the modulation of effort. However, to date, there is a lack of research to correlate oscillatory data with theories of effort and develop an understanding of the mechanism of force modulation under various task requirements. The article discusses possible studies on this topic and the features of the required experimental designs.

Keywords: mental effort, motivational intensity, brain oscillations, electroencephalography, magnetoencephalography, alpha rhythm, theta rhythm, complex tasks, motivation, cognitive abilities

Highlights

- The theory of motivational effort describes the non-linear dependence of the level of effort invested on the level of task complexity.
- studies of the cognitive mechanism of mental effort suggest a connection between brain oscillations and the phenomenon of effort.
- modulations in the severity of task-related oscillations appear to be consistent with motivational intensity theory.
- research oscillatory correlates of various cognitive processes can develop theories describing the mechanism of effort modulation.

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Introduction

Effort is a common feature of everyday life. Whether it's running to the bus stop, studying, or eating an unpleasant diet (Inzlicht et al., 2018). The required effort for these activities can be defined as the intensification of mental or physical activity to achieve some goal (Eisenberger, 1992). It is thus an active volitional process (Kahneman, 1973) that mediates between how well an individual can potentially perform a task and how well he actually performs that task (Shenhav et al., 2017). Effort is expressed in the intensity of behavior with a certain motivation, goal and conditions for achieving it. The degree of effort invested depends not only on motivation, but also on many other internal and external factors (Inzlicht et al., 2018; Shenhav et al., 2017).

Appearing in the 1970s, theories about effort continue to develop in recent years, which shows the importance and relevance of research into the nature of effort and the mechanisms of its modulation in the field of fundamental psychology. This article is devoted to the study of the mechanisms of force modulation, that is, the factors that determine the intensity of the applied effort. More specifically, we are interested in the intensity of mental effort invested in the performance of cognitive tasks, that is, in mental activity (Shenhav et al., 2017).

Modern authors suggest that not all cognitive processes require effort, while some may require more effort than others. The performance of any task is associated with the choice of the optimal level of effort for a given process, that is, with the distribution of effort among the processes (Shenhav et al., 2017). However, the nature of these restrictions, as well as the mechanism for the distribution of efforts, remains unclear - the authors of theoretical articles themselves put forward hypotheses. We believe that studies of brain oscillations can contribute to the understanding of the processes behind the distribution and modulation of efforts, as they allow us to consider the correlates of individual top-down processes. (Buzaki et al., 2012; Siegel et al., 2012).

In this article, we have tried to connect modern theories of effort with known data on the modulation of oscillatory correlates of cognitive tasks. Our task was to describe and combine two separate theoretical directions (the theory of motivational intensity and theories of mental effort), substantiate the hypothesis about the possibility of interpreting oscillations in terms of these theories, and review the existing experimental data in the context of these theories.

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Theoretical justification

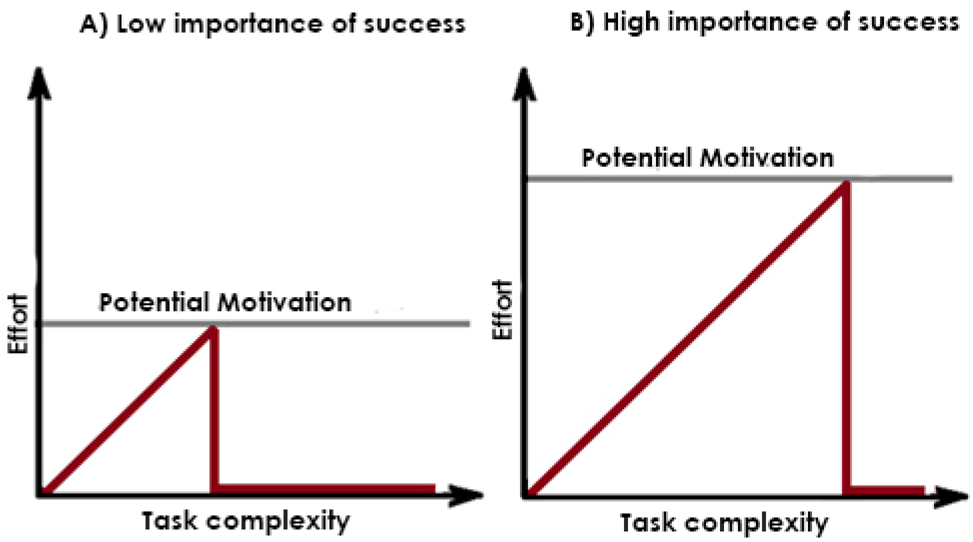
Mental effort. Definition and basic concepts

The concept of effort is necessary in order to explain the following phenomenon: when performing various tasks, it is common for people to not realize their physical or mental abilities to the fullest. For example, the introduction of rewards often improves the quality of task completion (Richter et al., 2016). Thus, the result of the task is determined not only by the ability of a person, but also by the degree of effort applied to its implementation.

There are several approaches to the definition and study of mental effort. Richter and colleagues define effort as the mobilization of resources to maintain a particular behavior (Richter et al., 2016). The authors consider effort in the context of Brehm's motivational intensity theory (Brehm & Self, 1989), which is based on the principle of resource conservation. Motivation intensity theory postulates that effort increases with increasing task complexity if success is possible and the effort is justified. At the same time, the level of effort drops sharply if the task becomes so difficult that, on the one hand, it exceeds human capabilities and makes success too unlikely, and, on the other hand, requires an unreasonably high level of resource mobilization (Brehm & Self, 1989). Thus, in accordance with the principle of conservation of resources, the intensity theory of motivation predicts a sharp decrease in effort when performing particularly difficult tasks. Potential Motivation - this is the hypothetical maximum effort that is justified and that a person is ready to make to complete the task. This indicator, in turn, depends on the significance of success for a person (Fig. 1) (Richter et al., 2016).

Figure 1

Motivational intensity theory predictions for low (A) and high (B) importance of success (modified figure, Richter et al., 2016).



In a number of studies testing the theory of intensity of motivation, the mobilization of efforts was assessed by fixing the physiological reactions of the cardiovascular system : the heart rate as a period of isovolumic contraction (cardiac pre-ejection period), systolic blood pressure, heart rate. Thus, it was shown that these reactions become more pronounced with an increase in the complexity of cognitive tasks and decrease sharply in conditions when the task is impossible (Richter et al., 2008 ; Gendolla and Richter, 2006 ; Smith, Baldwin and Christenson, 1990). At the same time, high motivation prevents the effect of the drop in effort (Eubanks, Wright & Williams, 2002), and too low motivation does not lead to an increase in effort (Wright, Shaw, and Jones, 1990). Thus, in these studies x the basic provisions of the theory are confirmed - the dependence of effort on the complexity of the task, the possibility of success and motivation (Wright, 1996).

Cognitive mechanism of effort modulation

In the Brehm et al., 1989 approach to explaining the phenomenon of effort, the key mechanism of effort is to increase the intensity of the overall motivation to complete the task (Brehm et al., 1989). In parallel with the theories described and empirical studies, theories of mental effort are being developed to explain the cognitive mechanism of effort modulation.

Mental effort is defined as a mediator between, firstly, the complexity of the task and the cognitive abilities of the subject, and, secondly, the final quality of information processing (expressed in reaction time and task accuracy) (Shenhav et al., 2017). The first two factors determine the potentially achievable level of task performance. Mental effort as an intermediate process influences the level of performance actually realized.

The cognitive mechanism that explains the nature of mental effort is associated with the idea of the need to involve executive functions (executive control functions) to control information processing processes with varying degrees of automation (Earle et al., 2015 ; Luria, 1980). Regularly repetitive stereotypic processes are well automated and require less effort, while those involving cognitive control require more effort (Botvinick & Cohen, 2015). This approach argues that a key function of effort is to maintain focus on the goals of the assignment and prevent them from being replaced by competing goals or being distracted by environmental factors. Thus, task characteristics may require different levels of activation of voluntary attention or the executive component of working memory (Kane & Engle, 2002), which in turn affects the amount of effort required for successful implementation.

The presence of an intermediate variable between cognitive abilities and the result of the task is explained by the limited resource necessary for the distribution and maintenance of controlled processes (cognitive control). There are several theoretical explanations for the limits on the amount and time of maintaining control. Among the factors explaining these limitations are the brain's limited metabolic resources (Muraven, Tice & Baumeister, 1998), as well as the limitations of information processing systems themselves - the occurrence of interference due to the need to use common processes for different tasks (Musslick et al., 2016).

Enough evidence that humans and animals avoid effort (Dreisbach & Fischer, 2015 ; Kool et al., 2010; Hull, 1943 ; Silvestrini, 2017). Many authors agree that effort is inherently unpleasant and costly, and they attribute this phenomenon to the need to conserve limited cognitive control resources (Inzlicht et al., 2018).

Theories of mental effort postulate the need for a mechanism to distribute control among various processes based on signals of necessary costs and opportunities. For example, Shenhav et al. (2017) develop the theory of the expected cost of control (expected value of control). This theory involves adjusting the necessary intensity of control and the choice of processes that need to be controlled. For this, the estimate the necessary costs of a limited resource and the likelihood of benefits (Shenhav et al., 2013)

Tasks requiring cognitive effort involve a network of cortical structures that includes the dorsal anterior cingulate cortex (ACC), insula, lateral prefrontal cortex, and lateral parietal cortex (Shenhav et al., 2013). The activity of these structures is more pronounced when performing tasks that require holding voluntary attention, retaining information in short-term memory, and suppressing automatic (dominant) responses (Power & Peterson, 2013). In general, the functions of these structures are associated with the distribution of controlled processes, although the specific functional roles of individual areas are discussed. In some models that explain the role of the dorsal ACC in the distribution of control, patterns of activity are correlated with a determination of the level of effort required (Shackman et al., 2011). The authors of the cost of control (EVC) theory suggest that the role of the brain structures involved in solving tasks requiring control (including the dorsal ACC) is to integrate the signals necessary to determine the cost of control and distribute the effort between controlled processes (Shenhav et al., 2016). The possibility of modulation by the frontal regions of the activity of the occipital regions during the performance of tasks on cognitive control is shown, for example, in the work of Cohen and van Gaal (2013). Using the Granger causality method, the authors showed that the cognitive control neural network sends downstream signals to touch areas. Mikhailova et al. (2021), analyzing directional connectivity in theta and alpha rhythms, also observed coherence descending from the frontal cortex to sensory areas when solving a working memory task. Thus, in terms of the cost of control theory, the effects of the distribution of effort can manifest themselves not only in the frontal areas associated directly with cognitive control, but also in other areas of the cortex associated with the implementation of controlled processes.

Thus, the authors associate the concept of mental effort with brain correlates of cognitive control processes. Cognitive control is expressed in various modulations of brain activity. In this article, we consider modulations of electroencephalographic (EEG) and magnetoencephalographic (MEG) oscillations. First of all, cognitive control is associated with the activation of the frontal theta rhythm (4 - 7 Hz) and suppression of the parietal alpha rhythm (8 - 13 Hz) (Pfurtscheller, 1977; Missonnier et al., 2006; Yordanova, Kolev & Polich, 2001), which will be discussed below. Based on this, it can be assumed that these correlates of the performance of complex cognitive tasks may reflect the modulation of mental effort. In the following sections of the article, we consider the oscillatory correlates of performing tasks that require executive functions as possible indicators of effort, derived from the described complementary theories.

Significance of studying oscillations as correlates of cognitive processes

At the physiological level, cognitive processes occur in the brain through the interaction between functionally specialized but widely distributed populations of neurons that form networks. This interaction occurs due to synchronization of membrane potential oscillations of neurons included in the network (neuronal oscillations; Siegel et al., 2012). EEG or MEG methods provide information about changes in extracellular potential in the cerebral cortex. This makes it possible to detect neuronal oscillations and obtain information about the course of cognitive processes with a high temporal resolution (Buzsaki et al., 2012). Thus, studying the modulations of EEG/

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MEG oscillations associated with the performance of cognitive tasks can help researchers find a common basis under seemingly different cognitive processes or, conversely, separate similar processes (Siegel et al., 2012).

For example, Richter et al. (2008) in their study of effort modulation during the Sternberg task on working memory used the responses of the cardiovascular system as an indicator of effort. Meanwhile, like other cognitive tasks, the Sternberg task requires the activation of many processes, such as stimulus encoding, stimulus retention in working memory, stimulus retrieval from working memory (Sternberg, 1996). Time-frequency analysis of oscillations associated with the execution of the Sternberg problem makes it possible to separate these processes (Wianda & Ross, 2019; Proskovec et al., 2019; Heinrichs-Graham & Wilson, 2015; Pavlov & Kotchoubey, 2021) and examine their relationship to task difficulty and motivation separately. Therefore, the study of task-related oscillations may allow one to relate various top-down cognitive processes to theories of effort, and thus develop an understanding of the cognitive mechanism of effort.

Below we show that numerous studies of oscillations associated with the performance of complex cognitive tasks are consistent with the mental effort theories described.

Results

Relation of oscillations to the complexity of the problem

In the reviewed studies, participants mainly perform the working memory tasks, the Sternberg task and the n- back task, because such tasks have several levels of difficulty. The performance of both tasks is associated with a relative increase in power (synchronization) of the theta rhythm (4–7 Hz) and a relative decrease in power (desynchronization) of the alpha rhythm (8–13 Hz; Klimesch et al., 2005). Both of these effects have traditionally been interpreted as correlates of activation of cognitive control, downward attention, or executive functions of working memory (Klimesch et al., 1998; Cohen & Donner, 2013; Sauseng et al., 2010).

In most studies, analysis of the power of alpha and theta rhythms shows synchronization of the theta rhythm and desynchronization of the alpha rhythm with increasing task complexity. Thus, the sensitivity of alpha rhythm desynchronization to changes in task complexity was shown in a study by Stipacek and co-authors (2003). Participants in the study completed a short-term memory task, which required memorizing and recalling sequences of numbers (three or five digits), and a working memory task, which also required additional manipulation of numbers (counting). In both tasks, with increasing complexity, desynchronization of the fast alpha rhythm increased, most pronounced in the posterior parts of the brain. In the short-term memory task, this pattern was more noticeable than in the working memory task.

A linear increase in both the relative and tonic (absolute) power of the frontal theta rhythm with increasing work memory load was also shown in a study by Zakrzewska and Brzezicka (2014). Study participants completed the Sternberg task, which required them to memorize two to five digits.

In a study by Gevins et al. (1997), study participants completed an n- back task with two difficulty levels: 1-back and 3-back. In the n- back task, participants are presented with a sequence of symbols and are required to answer whether the presented stimulus was encountered among the previous n symbols. The power of the theta rhythm in the median frontal region was higher in a difficult condition compared to an easy one. Also, the lower alpha rhythm (8 - 10.5 Hz) in the parietal region and the upper alpha rhythm (10 - 13.5 Hz) in the parietal-occipital region were

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more pronounced in the mild condition. In another study by Gevins et al. (1998), participants performed spatial and verbal versions of the n- back task. It was shown that with increasing task complexity, the power of the frontal theta rhythm increases, the power of the alpha rhythm in the parietotemporoccipital region decreases, and the power of the beta rhythm in the central region.

Increased depression of the central-frontal beta rhythm with the complication of the task was also found by Pavlova et al. (2019). The linguistic task used required the extraction of the verb from semantic memory. The participant had to name the associated verb in response to the noun. Complexity was regulated by the number of possible associations. The suppression of the beta rhythm was interpreted by the authors as an increase in the level of effort upon activation of the semantic-motor association.

In a study by Scheeringa and colleagues (2009), participants completed the Sternberg task, in which the length of a sequence varied from zero to seven consonants. With an increase in the complexity of the task, an increase in the power of the posterior alpha rhythm and an increase in the power of the frontal theta rhythm during the retention of information in working memory were observed.

An increase in the power of the frontal theta rhythm with increasing task complexity was also obtained using the Sternberg problem, in which the number of letters in the encoded sequence varied from one to four (Gundel & Wilson, 1992).

Using the machine learning method, Goryushko and Samochadin (2018) created a classifying model that determines the degree of cognitive load according to the severity of the background theta rhythm. The experiment used the Sternberg problem, which includes from two to ten consonants. Result of this experiment indicates a positive relationship between the power of the theta rhythm and the level of task complexity.

Not only a decrease, but also an increase in the power of the alpha rhythm may be necessary to perform complex cognitive tasks. Scheeringa and colleagues found an increase in posterior alpha power synchronization with increasing difficulty in the Sternberg task (Scheeringa et al., 2009). The authors explain the regularity obtained by the hypothesis of the relationship between the power of the alpha rhythm and the downward functional inhibition of areas that disrupt the process of retaining information in working memory. The hypothesis about the role of the alpha rhythm in the maintenance of working memory was tested by Bonnefond and Jensen (2012). In the study, participants performed a modified Sternberg task involving distractors (distracting stimuli) in the retention period. The power of the alpha rhythm in the temporo-occipital region has been shown to increase in anticipation of a distractor. Increased alpha power during this period also predicted better task performance.

In the described studies, linear relationships were observed between oscillatory correlates and task complexity. Such dependences only allow us to draw a conclusion about the relationship of these correlates with cognitive load. And x is not enough to prove the connection of these correlates with motivation and theories of effort. Recently, however, the first studies have appeared that use very complex levels of tasks and have obtained non-linear dependencies that can no longer be explained solely by cognitive load. Such an effect of increasing the level of difficulty of tasks on the modulation of oscillations is shown in the study by Fairclough and Ewing (2017) and Fairclough et al. (2019). Members performed back n- backs at three difficulty levels (easy n = 1, difficult n = 4, very difficult n = 7). The power of the frontal medial theta rhythm increased from a simple conditions to difficult and again decreased to very difficult. Similar results were obtained for the alpha rhythm: depression of the alpha rhythm was most pronounced under difficult conditions (n = 4) and decreased under simple and very difficult conditions (n = 1 and n = 7). Recent results provide an argument for linking occipital-parietal alpha depression and frontal theta activation with effort in the context of motivational intensity theory.

This article is devoted to the oscillatory correlates of the performance of cognitive tasks. Such correlates reflect the prolonged activity of the cortex associated with the implementation of cognitive processes. However, it is important to note that EEG studies of stimulus-related evoked potentials (Nidal & Malik, 2014) are also consistent with oscillation studies. Thus, many studies have found an increase in the amplitude of various components of the evoked potential with an increase in the complexity of the task (Koshkin et al., 2018; Pavlova et al., 2017; Shelepin et al., 2009). At the same time, under particularly difficult conditions, a drop in the amplitude of the P3 component associated with high-level processing of the stimulus was observed (Johannes et al., 2021).

Similar results have been shown in other studies of oscillations, but only for certain groups of subjects, these studies will be described below.

Influence of Motivation on Oscillatory Correlates of Cognitive Task Performance

According to the motivational intensity theory, the alpha and theta correlates of cognitive task performance increase as rewards for success increase (Glazer et al., 2018). In the conditions of x expectation of a reward, there is an increased desynchronization of the parietal-occipital alpha rhythm associated with stimulus evaluation, expectation of feedback (Bastiaansen, 1999; Bastiaansen, 2001; Pornpattananangku l & Nusslock, 2016), performing an n- back task on working memory (Fairclough & Ewing, 2017) and Stroop tasks on cognitive control (van den Berg et al., 2014). The authors interpreted these results as increased attention with increased motivation to complete the task.

More controversial results have been obtained regarding the frontal theta rhythm as the main correlate of the performance of complex cognitive tasks (Glazer et al., 2018). Some authors have found an increase in the power of the frontal theta rhythm associated with stimulus coding in working memory with increased reward (Gruber et al., 2013), while others found no such association (Fairclough & Ewing, 2017). Knyazev and Slobodskoy-Plusnin (2009) showed that the relationship between the frontal theta rhythm and expectation of reward or punishment depends on intrinsic sensitivity to reward or punishment. Hypothetically, this result may explain the controversial data on the relationship between theta rhythm and motivation.

There is also evidence of increased desynchronization of the alpha rhythm and synchronization of theta rhythm associated with stimulus coding, with increased intrinsic motivation (Pukhachee et al., 2019 ; Ermakov & Vorobyeva).

The relationship of the observed EEG correlates with the theory of motivational intensity can also be assumed when studying the individual differences of the subjects. The conflicting results of studies focusing on individual differences in the modulation of brain activity depending on the complexity of the task are described below, and the possible resolution of contradictions when paying attention to the motivational characteristics of the subjects is explained.

Studies on the relationship between EEG correlates of task performance and intelligence also paradoxically lead to a hypothesis about the relationship of these indicators with the motivation of the subjects. Subjects with a high level of intelligence or high accuracy of answers have

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a reduced desynchronization of the alpha rhythm associated with the performance of tasks for logical thinking and memory (Neubauer & Fink, 2009; Neubauer et al., 1995; Jausovec, 1996; Vogt et al., 1998; Jausovec, 2000 ; Stankova and Myshkin, 2016). The authors attribute this phenomenon to the neuronal efficiency hypothesis. According to hypothesis, more capable subjects tend to process information more efficiently and can complete tasks with fewer resources and less mental activity (Neubauer & Fink, 2009; Jausovec, 2000). Confirmation of this hypothesis was also obtained in the analysis of theta-correlates of task performance (Doppelmayr et al., 1998; Karatygin N.A. _ al., 2022). It is worth noting that the effect of neuronal efficiency does not contradict the modern theory of motivational intensity. According to the authors of the theory, more capable subjects invest less effort in performing simple tasks (Richter et al., 2016). However, other studies have shown the opposite effect, demonstrating increased alpha desynchronization in subjects with high levels of intelligence or high response accuracy (Doppelmayr et al., 2005; Grabner , Neubauer & Stern, 2006; Klimesch et al., 2007; Jausovec & Jausovec, 2005; Belousova, Razumnikova and Wolf, 2015). These studies used memory tasks, as well as logical and spatial thinking tasks. Explaining the effect obtained, the authors suggest that people with high abilities demonstrate more efficient brain function, that is, they have access to more resources, which allows them to solve more complex problems.

Separate studies have also shown that the difference in activation of the parietal cortex between groups of subjects with high and average levels of intelligence depends on the level of task complexity. These studies used analytical and figurative thinking tasks. Desynchronization of the alpha rhythm (Doppelmayr et al., 2005; Hanslmayr, 2005) as well as amplification of the fMRI signal (Preusse et al., 2011; Perfetti et al., 2009) have been interpreted as an increase in cortical activation required to perform a task. For simple tasks, a neuronal efficiency effect was observed. For complex tasks, the opposite effect was observed - an increase in cortical activation in capable subjects, and a downward trend in less capable subjects. Such a trend can be explained by the drop in effort in less capable subjects who view difficult tasks as not worth a large cognitive cost.

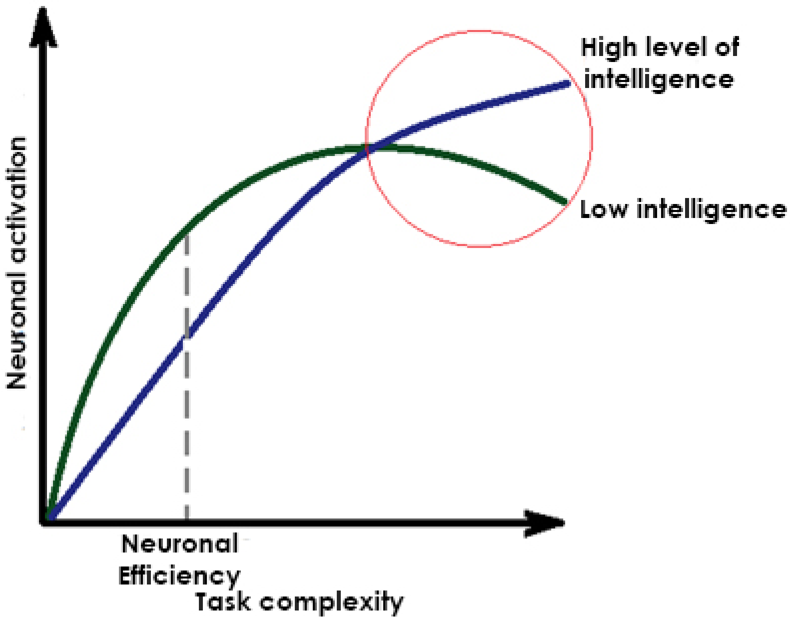
A similar phenomenon was obtained for the theta rhythm as a correlate of the performance of the Sternberg task (Pavlov & Kotchoubey, 2017). The authors analyzed the relationship between the power of the theta rhythm and several levels of task complexity: memorization of five to seven letters in the presence of their manipulation in working memory. The power of the theta rhythm steadily increased with the complexity of the task only in subjects with high accuracy of answers. In subjects with low accuracy, the power of the theta rhythm decreased under the most difficult condition of the task. The authors suggested two explanations for this difference in theta rhythm modulation between groups. Perhaps the less capable subjects were not able to use the required amount of required resources to complete the most difficult level of the task. That's why they resorted to changing the strategy to a less resource-intensive one. Another explanation is the drop in effort in less capable subjects under the most difficult condition, associated with reduced motivation to complete the task.

Thus, the described individual differences in alpha and theta modulations can be explained both by the effect of the reached ceiling and by the effect of the drop in effort due to lack of motivation.

Larson et al (1995) supports the second explanation. The authors compared PET activation in subjects with high and average intelligence a. PET activation increased in subjects with high intelligence when the task became difficult. At the same time, in subjects with an average level of intelligence, activity decreased. For all subjects, the authors used the conditions of subjective complexity : easy task - 90% correct answers, difficult task - 75%. Thus, the authors leveled the impact on the results of the cognitive abilities of the subjects - the tasks were equally difficult for all subjects in the easy and difficult conditions. The observed difference in the modulation of brain activity between groups of subjects can be explained more by their different reactions to a high level of subjective complexity than by the level of intelligence itself. This dependence can be explained by the level of motivation to perform a complex task y, which differs for more and less able x test subjects (Larson et al., 1995; Neubauer and Fink, 2009). At the same time, decreased brain activity As well as the deactivation of the alpha rhythm, in subjects with high intelligence when performing the simplest tasks, the authors explained the effect of neuronal efficiency, that is, cognitive differences (Fig. 2).

Figure 2

Dependence of brain activation on task complexity (modified figure, Neubauer & Fink, 2009). The authors suggest that at the most difficult levels of the task, the effects of motivation and emotional reaction to complexity are manifested. This effect (highlighted with a circle) is well explained by the theory of motivational intensity.



The described effects are well explained by the described theories of effort: in subjects less motivated to perform a complex task, the effect of reducing the effort invested in conditions of increased complexity is observed. To date, there have been no similar studies focusing on brain oscillations associated with task performance. However, based on studies of oscillations and individual differences described above, it is logical to assume that a similar effect should be observed for the oscillatory correlates of top - down cognitive processes. The severity of these oscillations should increase with the complexity of the task, but fall in particularly difficult conditions in subjects with low motivation. To test these hypotheses, further studies of oscillatory correlates of various top - down processes and their dependence on the subjective complexity of the task. This should take into account the cognitive abilities and the level of motivation of the subjects. By motivation we mean both external and internal, both situational and personal, including, in particular, the level of self-confidence.

Discussion

Summarizing the known theories of effort, we can draw the following conclusions. Cognitive effort determines the expenditure of limited cognitive resources to perform tasks that require complex top-down cognitive processes. Cognitive effort increases with the complexity of these tasks until the task becomes unnecessarily difficult. The determination of this critical level of difficulty, at which there is a drop in effort, is influenced by the level of motivation to succeed.

Summarizing studies analyzing the relationship between the power of oscillatory correlates of cognitive processes and the complexity of the task, motivation, and cognitive abilities, we can draw the following conclusions. These spectral indicators can be modulated in accordance with the theoretical provisions described, and, therefore, can reflect mental effort. The main oscillatory correlates of performing complex cognitive tasks are synchronization of the frontal theta rhythm (generally interpreted as activation of executive control) and desynchronization of the posterior alpha rhythm (generally interpreted as activation of controlled attention). According to theories of mental effort, these processes are directly related to the process of distribution of effort in the performance of a task. The severity of these oscillatory effects increases with the complexity of the tasks. At the same time, under conditions of the most complex tasks, the level of expression of these oscillations is presumably influenced by motivation. Presumably, less motivated subjects show a decrease in the severity of these correlates. This effect is explained by a drop in the level of effort invested according to the theory of motivational intensity and is consistent with theories of mental effort.

The study of oscillatory correlates of various cognitive processes will expand the understanding of the neuronal foundations of cognitive effort and the relationship of effort with various cognitive functions. Since oscillatory measures allow researchers to isolate the correlates of individual cognitive processes, such studies will expand the understanding of the cognitive mechanism responsible for the distribution of effort.

Currently, there are practically no studies that test the described hypotheses. A review of the literature showed that researchers rarely use tasks with a large variability in complexity in experiments, including both very simple and very complex conditions. However, in order to reveal the effects of an increase in effort with increasing complexity of the task and a decrease in effort with an unreasonably complex task, the experimental problem must have many levels of complexity. The greatest interest for this area of research is not the objective, but the subjective complexity of the problem, since the modulations of effort associated with it will not be explained by cognitive abilities. Therefore, they can be explained by the influence of emotional and motivational aspects. It is necessary to select the complexity conditions so that when the task becomes more complicated, the maximum number of subjects demonstrate a decrease in the quality of performance to the level of random guessing. This will provide an opportunity to test the hypothesis of a decrease in oscillatory effects under the condition of maximum subjective complexity.

Also, for such studies, the correct choice of the task is necessary, taking into account the cognitive processes that it requires, and their known oscillatory correlates. The problem should allow the dissociation of the correlates of different processes either by their frequency range or by their time period. For example, the n- back task requires the simultaneous activation of the process of encoding relevant and the process of suppressing irrelevant information, resulting in desynchronization and synchronization of the alpha rhythm, respectively. This leads to confusion between the correlates of the two processes and unclear results (Klimesch, Schack & Sauseng, 2005). While the Sternberg problem, for example, allows you to separate the processes of encoding, retention, and retrieval of information from working memory. Many of the studies described have analyzed only general desynchronization of the alpha rhythm as an indicator of cortical activation. Such studies can be performed with other methods of measuring cortical activation, so they are consistent with data from fMRI and PET studies (for example, Bekhtereva et al., 2000; Kharauzov et al., 2018). However, we propose to use EEG and MEG methods with high temporal resolution to study the relationship of individual cognitive processes with effort modulation.

Also, to date, there are not enough studies analyzing the influence of motivation on oscillatory effects associated with the performance of tasks of varying complexity. Research on this topic should include various indicators of intrinsic and extrinsic motivation as a factor that determines the modulation of effort under conditions of particularly complex tasks. An analysis of the influence of the level of motivation on the severity of the effects, taking into account the level of complexity of the task, should show the connection between these effects and the theory of motivational intensity. Finding different relationships between these variables, as well as finding different relationships for different types of motivation, will help develop an understanding of the mechanism of distribution of effort in the face of complex tasks.

Conclusion

According to the theory of motivational intensity, the degree of effort invested in the performance of a task depends on the estimated subjective complexity of the task and the motivation to complete the task.

Theories describing the cognitive mechanism of mental effort suggest a connection between oscillations as correlates of controlled cognitive processes and the phenomenon of effort.

Modulations in the severity of task-related oscillations (such as frontal theta synchronization and parietal alpha desynchronization) appear to be consistent with motivational intensity theory. A review of existing research shows a non-linear dependence of these oscillations on the complexity of the task and individual differences in this dependence. These effects can be explained by the influence of the motivational-emotional characteristics of the subjects in the context of the theory of motivational intensity. However, to date, there are not enough correct studies to confidently confirm these hypotheses.

The study of oscillatory correlates of cognitive task performance can help develop theories describing the mechanism of effort distribution and modulation by correlating theories with individual cognitive processes.

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Author Contribution

Natalia Aleksandrovna Zhozhikashvili – idea, guidance, literature analysis, writing the text of the article.

Anna Denisovna Bakumova - participation in discussions, literature analysis, writing the text of the article.

Author Details

Natalia Aleksandrovna Zhozhikashvili - trainee researcher, National Research University Higher School of Economics, Moscow, Russian Federation; Researcher ID: ABI- 2353-2020 Scopus Author ID: 57194142568, ORCID: https://orcid.org/0000-0002-8405-8722 ; e-mail : nzhozhik@gmail.com
Anna Denisovna Bakumova - trainee, Psychological Institute of the Russian Academy of Sciences, Moscow, Russian Federation ; ORCID: https://orcid.org/ 0000-0001-5346-785X ; e-mail : bakumovaanna@gmail.com

Information about the conflict of interest

The authors declare no conflict of interest.