

Identification of the Oculo-Motor System in the Form Volterra Model Based on Eye-Tracking Data

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Abstract. Instrumental computing and software tools have been developed for constructing a nonlinear dynamic model of the human oculo-motor system (OMS) based on the data of input-output experiments using test visual stimulus and innovative technology. Volterra model in the form of multidimensional transition functions of the 1st, 2nd and 3rd orders, taking into account the inertial and nonlinear properties of the OMS was used as the identification tool. Eye-tracking data developed in the Matlab environment are tested on real datasets from an experimental study of OMS.

1 Introduction

The study of human eye movements and the trajectory of their movement allows us to reveal the structure of the relationship of an individual with the environment, a person with the world. Knowledge about eye movement is of great theoretical and applied importance, expanding the possibilities of studying the specifics of many professions in order to improve the efficiency of the subject of labor activity [1-4].

The process of mastering knowledge is a central part of the learning process. Managing this process implies the existence of effective objective indicators for assessing an individual's intellectual abilities. The methods of psychological identification of an individual proposed in the project based on obtaining experimental data using the innovative Eye-tracking technology and computing means of processing them allow monitoring and diagnostics of the state of cognitive processes during the educational activities of students [5-9].

The aim of this work is to develop instrumental software tools for constructing a nonparametric dynamical model of the OMS human, taking into account its inertial and nonlinear properties, based on data from experimental input-output studies using test visual stimulus and innovative eye-tracking technology; implementation of the received information models in practice diagnostics of states cognitive processes.

1.1 The scope of application

The developed software enables support of the following tasks:

- The relationship study of mental states and cognitive processes in educational activities, a post-traumatic stress disorder, the diagnosis of the Parkinson's and Alzheimer's disease stage, checking the psychophysiological state of pilots and drivers, the professional suitability, the fatigue syndrome [10-16].

- The interaction of mental states and cognitive processes during the educational activities of students, an objective assessment of their cognitive development level, assessment of the effectiveness of training to improve mental processes and for psychological correction of personality [16].

- Extension of the individual's creative life due to the early diagnosis of degenerative processes of cognitive functions of the brain. Identification of a gifted personality (building a psychological model of the personality) and evaluation of its abilities. Professional selection (the identification and education of leaders) [9].

- The assimilation of scientific knowledge and their respective skills serves as the main goal and the main result of educational activities. The process of mastering knowledge is the central part of the learning process. Managing this process implies the existence of effective objective indicators for assessing an individual's intellectual abilities [7].

The methods of psychological identification of an individual proposed in the project, based on obtaining experimental data using eye tracking technology and computing means of processing them, allow monitoring and diagnostics of the state of cognitive processes during the educational activities of students.

1.2 Diagnostics neuronal processes

An intelligent information technology for diagnosing the states of neural processes based on nonparametric identification of OMS in the form of nonlinear dynamic Volterra models is proposed [17, 18]. The technology involves a consistent solution of the following tasks:

- *Identification of the OMS.* The goal is to obtain an OMS information model in the form of MTF. *Stages of implementation:* the supply of test signals to the inputs of the OMS (horizontally, vertically, diagonally); measurement of OMS responses to test signals with the

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help of an eye-tracker; MTF calculation based on input-output experiment data.

– *Building a diagnostic model of OMS.* The goal – the formation of the feature space. *Stages of implementation:* MTF compression; determination of the diagnostic value of symptoms; selection of the optimal system of signs – reduction of the diagnostic model.

– *Building a classifier of the psycho-physiological state of the individual based on the OMS model.* The goal is to build a family of decision rules for optimal classification. *Stages of implementation:* building decision rules based on OMS identification results – training; assessment of the accuracy of the classification – the exam; optimization of the diagnostic model.

– *Diagnostics psycho-physiological state of the personality.* The goal is to assess the condition of the individual. *Stages of implementation:* OMS identification; evaluation of diagnostic signs; classification – the assignment of the investigated individual to a particular class.

2 Approximation Volterra model of the nonlinear dynamical system

The input-output ratio for a nonlinear dynamical system (NDS) with an unknown structure (such as a "black box") with a single input and a single output can be represented by a discrete cubic Volterra polynomial in the form [17]:

$$y[m] = \sum_{n=1}^3 y_n[m] = \sum_{k_1=0}^m w_1[k_1]x[m-k_1] + \sum_{k_1=0}^m \sum_{k_2=0}^m w_2[k_1, k_2]x[m-k_1]x[m-k_2] + \sum_{k_1=0}^m \sum_{k_2=0}^m \sum_{k_3=0}^m w_3[k_1, k_2, k_3]x[m-k_1]x[m-k_2]x[m-k_3], \quad (1)$$

where $w_1[k_1]$, $w_2[k_1, k_2]$, $w_3[k_1, k_2, k_3]$ – discrete weight functions (Volterra kernels) of the 1st, 2nd and 3rd orders; $x[m]$, $y[m]$ – input (stimulus) and output (response) function (signals) of the system, respectively; $y_n[m]$ – partial components of the response (convolution of n -th order sequences); m is a discrete time variable.

The problem of identification is to choose test signals $x[m]$ and develop an algorithm that allows based on the responses received $y[m]$ to identify partial components $y_n[m]$, ($n = 1, 2, 3$) and determine on their basis multidimensional Volterra kernels: $w_1[k_1]$, $w_2[k_1, k_2]$, $w_3[k_1, k_2, k_3]$ [18].

Taking into account the specifics of the studied OMS, test step signals are used for identification. If the test signal $x[m]=\theta[m]$, where $\theta[m]$ is a unit function (Heaviside function), then the partial components of the response $y_1[m]$, $y_2[m]$, $y_3[m]$ will be equal to the transient function of the first order $h_1[m]$ and diagonal

sections of the transient functions of the second and third orders $h_2[m, m]$, $h_3[m, m, m]$, respectively [19-22]:

$$y_1[m] = h_1[m] = \sum_{k_1=0}^m w_1[m-k_1],$$

$$y_2[m] = h_2[m, m] = \sum_{k_1=0}^m \sum_{k_2=0}^m w_2[m-k_1, m-k_2], \quad (2)$$

$$y_3[m] = h_3[m, m, m] = \sum_{k_1=0}^m \sum_{k_2=0}^m \sum_{k_3=0}^m w_3[m-k_1, m-k_2, m-k_3].$$

Determination of subdiagonal intersections of transient functions is based on the NDS test using L test step signals with given amplitudes a_i , $i=1, 2, \dots, L$ ($L \geq N$, N is the degree of the Volterra polynomial). In this case the responses of the NDS are denoted by $y_1[m]$, $y_2[m]$, \dots , $y_L[m]$. Reviews of the Volterra model will be view

$$\tilde{y}_i[m] = a_i \hat{y}_1[m] + a_i^2 \hat{y}_2[m] + a_i^3 \hat{y}_3[m], \quad i = \overline{1, L}, \quad (3)$$

where $\hat{y}_1[m] = \hat{h}_1[m]$, $\hat{y}_2[m] = \hat{h}_2[m, m]$, $\hat{y}_3[m] = \hat{h}_3[m, m, m]$ – obtained estimates of the partial components of the model – multidimensional transition functions.

To determine the transition functions $h_1[m]$, $h_2[m, m]$, $h_3[m, m, m]$ is used the method of least squares (LSM), which provides the minimum standard error of the deviation of the model responses from the responses of the OMS to the same stimulus:

$$J_N = \sum_{j=1}^L \left(y_j[m] - \sum_{n=1}^N a_j^n \hat{y}_n[m] \right)^2 \rightarrow \min. \quad (4)$$

The minimization of criterion (4) is reduced to solving a system of normal Gaussian equations, which in vector-matrix form can be written as

$$A' A \hat{y} = A' y, \quad (5)$$

where $A = \|\alpha_{ij}\|$, $\alpha_{ij} = a_i^j$, $i, j = \overline{1, N}$.

3 Computing of transient functions OMS

Information technology of the constructing a nonparametric dynamic model of the human OMS taking into account its inertial and nonlinear properties based on the data of experimental studies input-output was developed. As a basic OMS model – the Volterra model is used in the form of multidimensional transition functions.

Methods and tools for the identification of OMS have been developed using the help of eye tracking technology, and building a features space and optimal classification human states using machine learning. In the Laboratory of Motion Analysis and Interface

Ergonomics at the Lublin University of Technology (Lublin, Poland), joint studies of the human OMS were performed to obtain diagnostic information for solving urgent problems in the neuro informatics and the computational neuroscience. Experimental research was carried out using eye tracking technology with the use of the video based Tobii TX300 (300 Hz sampling rate) eye tracker and appropriate software [16].

The following instrumental algorithmic and software tools are developed to achieve the goal of the research:

- Formation of test signals in the form of bright dots on the computer monitor screen at different distances from the initial position horizontally, vertically and diagonally.
- Preprocessing (bringing the OMS responses to a common start and rationing to one) and analyzing the data obtained from the eye tracker.
- Constructing an identification model of OMS in the form of multidimensional transitional functions (integral transformations of Volterra kernels).
- Visualization of data and processing results of experimental research.

3.1 Experimental research of the OMS

When conducting experimental studies, such actions are carried out:

- The test subject is placed in front of the computer so that his eyes are at the center of the monitor at a distance of 40-50 cm from him.
- The subject's head is fixed in order to prevent its movements during the study and to ensure the same experimental conditions.
- On the subject's readiness, the Signal Manager of the test visual stimulus program is launched.
- A red circle appears in the center (or from its edge) – of the screen in the starting position.
- After a short pause (2-3 sec.), the circle in the starting position disappears and a circle of a different color appears at the point with the specified coordinates – a visual stimulus (test signal), which is displayed in this position for a specified duration (1-2 sec.) – the action makes the eye move in the direction of the visual stimulus.
- Then this stimulus circle disappears and a red circle appears in the starting position – this makes the eye move in the opposite direction to the starting position, after these actions the experiment ends.
- Using the eye tracker, the coordinates of the pupil of the eye are determined during its movement (reaction to the visual stimulus) in the period between the starting positions and the coordinate values are stored in the xls-file.

In the studies of each respondent, three experiments were successively implemented for three amplitudes of test signals in the horizontal direction. The distance between the starting position and the test incentives is equal to: $0.33 l_x$, $0.66 l_x$, $1.0 l_x$, where l_x is the length of the monitor screen. Coordinates of the starting position ($x = 0$, $y = 0.5 l_y$), l_y – mean the width of the monitor screen.

The obtained results of measurements of the OMS responses at $L=3$ obtained with using the Tobii TX300 eye tracker in one study cycle ("Horizontally") are shown in Figure 1. Transient process in the OMS response to the test signal $a_1 = 0.33$ are illustrated on Figure 2.

4 Results

The experiments were organized in order to classify subjects by the state of fatigue. The data for constructing the model – the OMS responses to the same test signals, were obtained using the Tobii Pro TX300 eye tracker at different times of the day: "In the Morning" (before work) and "In the Evening" (after work). The average values of the OMS responses obtained from the eye tracker at various amplitudes of the test signals "In the Morning" and "In the Evening" are shown in Figure 3.

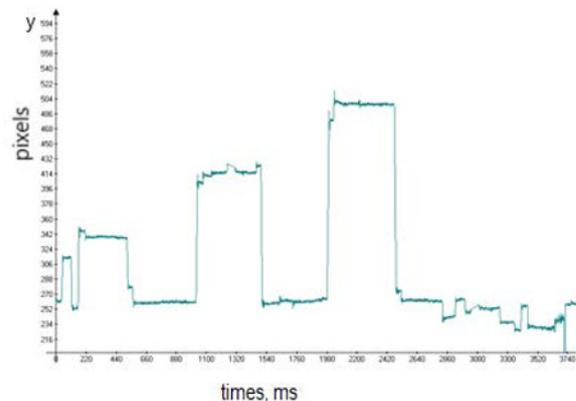


Fig. 1. OMS responses at $L=3$ obtained using the Tobii TX300 eye tracker

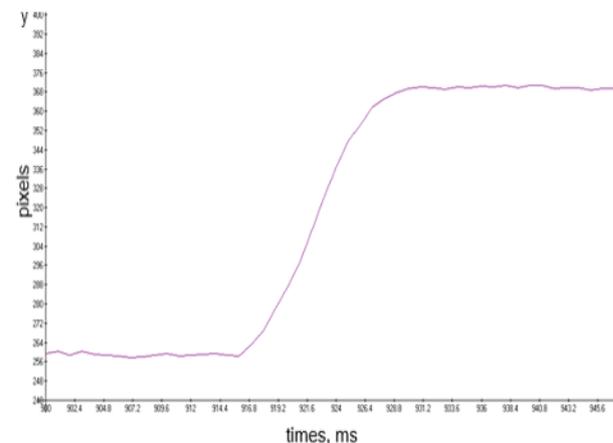


Fig. 2. Transition process in the OMS response to the test signal: $a_1 = 0.33$

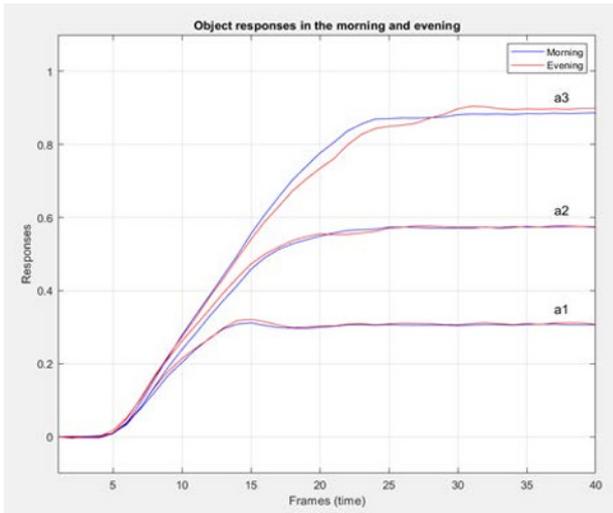


Fig. 3. Averaged OMS responses at various amplitudes of test signals "In the Morning" and "In the Evening"

According to averaged data of OMS responses on visual stimuli with a different distance from the start position on the basis of formula (5) the functions of the OMS were defined when approximation models of degrees $N = 3$ were used. Graphs of the transition functions estimates for the "In the Morning" and "In the Evening" states of the subject based on model (1) are shown in Figure 4.

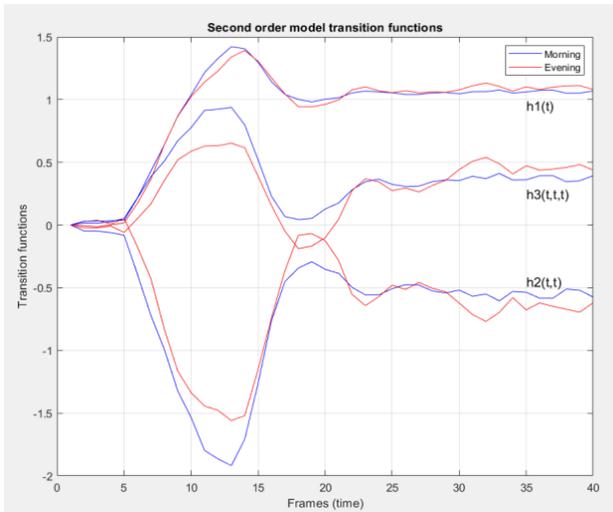


Fig. 4. Transition function estimates of the 1st, 2nd, and 3rd orders ($N = 3$) for states of the test subject "In the Morning" and "In the Evening"

Received responses with the help of calculations on models at $N = 3$ from various amplitudes of test signals "In the Morning". Graphs these are presented in comparison with similar responses OMS in Figure 5. Graphs of responses of the model OMS at $N = 3$ at various amplitudes of the test signals "In the Morning" and "In the Evening" are illustrated in Figure 6.

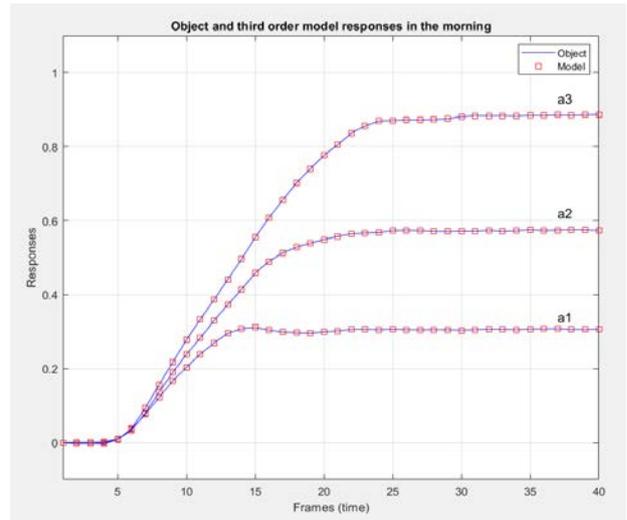


Fig. 5. Responses of the OMS and the model at $N = 3$ at various amplitudes of the test signals "In the Morning"

4.1 Deviation of the transient functions

The variability (deviation) of the MTF of different orders n of the approximation model of OMS for the states of the respondent "In the Morning" and "In the Evening" is quantified using the indicator of ε_{nN} – normalized standard deviation (6). The indicators deviation of the MTF of different orders n of the OMS approximation model for respondent states "In the Morning" and "In the Evening" are given in Table 1 and are represented by diagram in Figure 7.

$$\varepsilon_{nN} = \left(\frac{\sum_{m=0}^M (\hat{y}_{ne}[m] - \hat{y}_{nm}[m])^2}{\sum_{m=0}^M (\hat{y}_{nm}[m])^2} \right)^{1/2}, \quad n = \overline{1, N}. \quad (6)$$

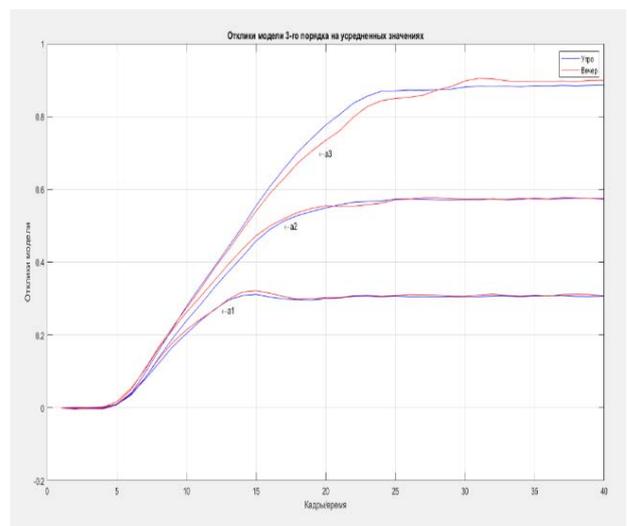


Fig. 6. The responses of the model at $N = 3$ at various amplitudes of the test signals "In the Morning" and "In the Evening"

Table 1. The deviation indicators of multidimensional transient functions

N	ε_{1N}	ε_{2N}	ε_{3N}
1	0.019	–	–
2	0.051	0.232	–
3	0.04	0.199	0.322

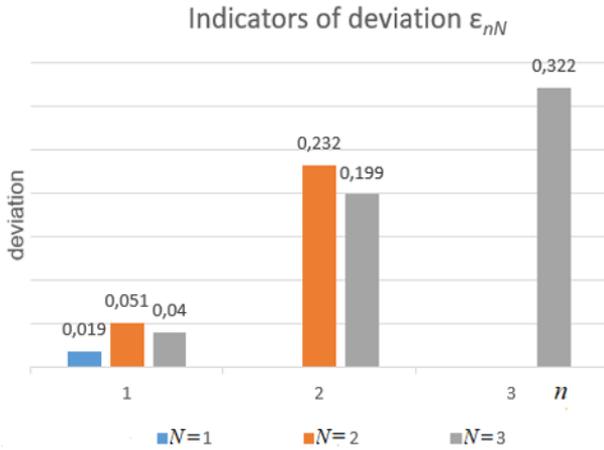


Fig. 7. Diagram of deviations indicators ε_{nN}

As can be seen from figure 5, the obtained transition function of the 1st order for the "In the Morning" and "In the Evening" are virtually independent of the status of the subject. However, the diagonal cross section of the transition functions of the second and third order change significantly in magnitude and, therefore, can be effectively used as the primary data source when building models of classifiers of psychophysiological conditions of the person using machine learning

4.2 Building a classifier of the fatigue

For estimate psycho-physiological state of the individual based on the OMS model conducted researchers:

- Building a feature space for designing the status classifier of a human using machine learning.
- Classifiers construction using deterministic and statistical methods of learning the pattern recognition based on the data obtained using eye tracking technology.

On base of training sets of data for an object's classes **A** ("In the Morning"), **B** ("In the Evening") there successively calculate discriminant function $d(\mathbf{x})$. To separate the two classes (dichotomy case) it uses discriminant function [23-25] of the form:

$$d(\mathbf{x}) = \frac{1}{2} \mathbf{x}'(\mathbf{S}_2^{-1} - \mathbf{S}_1^{-1})\mathbf{x} + (\mathbf{S}_1^{-1}\mathbf{m}_1 - \mathbf{S}_2^{-1}\mathbf{m}_2)'\mathbf{x} + \frac{1}{2}(\mathbf{m}_1'\mathbf{S}_1^{-1}\mathbf{m}_1 - \mathbf{m}_2'\mathbf{S}_2^{-1}\mathbf{m}_2 + \ln \frac{|\mathbf{S}_2|}{|\mathbf{S}_1|}) + \lambda_{\max} \quad (7)$$

where $\mathbf{x}=(x_1, x_2, \dots, x_n)'$ – features combination, n – features space dimensionality, \mathbf{m}_i – mathematical expectation vector for a features of class i , $i=1, 2$; $\mathbf{S}_i=M[(\mathbf{x}-\mathbf{m}_i)(\mathbf{x}-\mathbf{m}_i)']$ – covariance matrix for class i ($M[]$ – mathematical expectation operation), \mathbf{S}_i^{-1} – matrix

inverse to \mathbf{S}_i , $|\mathbf{S}_i|$ – matrix determinant \mathbf{S}_i , λ_{\max} – classification threshold that provides the highest criterion probability of the correct recognition of objects in the training sample.

The analysis of the quality of the combination of various features on base of the criterion probability of the correct recognition (P) is made. Quality of selected features combination from considered features set is evaluated by the result of classification on examination sample of data. A Bayesian classifier of a person's fatigue state in the space of features x_1 and x_2 :

$$x_1 = \arg \max_t h_1'(t), \quad x_2 = \arg \min_t h_1'(t). \quad (8)$$

The estimation of the indicator of recognition reliability is $P = 0,9375$.

The classification of this data by the support vector method (SVM) [26] with a quadratic separating function in the space of features x_1 and x_2 gives the same value of the probability of correct recognition ($P = 0,9375$). The location of the objects of the training set in the space of features x_1 and x_2 is shown in Figure 8.

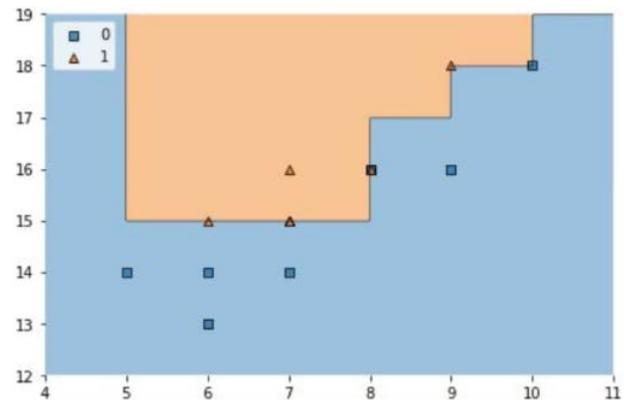


Fig. 8. The location of the objects of the training set in the space of features x_1 and x_2

5 Conclusions

Method and software have been developed for constructing a nonparametric dynamical model of the OMS human, taking into account its inertial and nonlinear properties, based on experimental input-output data using test visual stimuli and innovative eye-tracking technology. A nonlinear dynamic model in the form of a Volterra polynomial was used. The developed model was tested on real datasets from an experimental study of OMS.

Test visual stimulus in the form of bright points that are consistently displayed at different distances from the starting position are used. This formally corresponds to the different amplitudes of the step test signals. The transition functions of the 1st, 2nd, and 3rd orders are determined using LSM.

The developed software tools for data processing of the eye-tracking are tested on real data from an experimental study of the OMS. Verification of the constructed model confirms the adequacy model of the

investigated OMS – a practical coincidence (within an acceptable error) of the responses of the OMS and its model at the same test signal.

The revealed variability of the transition functions of the 2nd and 3rd orders for different psychophysiological states of the respondent (level of fatigue) has observed. Thus, they can be used in diagnostic studies in the field of the neuroscience and psychology.

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