The Functioning of the Brain Trained by Neurofeedback with Behavioral Techniques from a Learning Curve Perspective

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Abstract: The learned reflex behavior (Reaction) of Ivan Pavlov (1849-1936) and operant behavior (Action) of Burrhus Skinner (1904-1990) have been used as technical approaches from the perspective of the learning curve through repetitious training using neurofeedback. The aim of this study was to describe the meaning and application of these associated approaches and to explain their neurophysiological implications. A review of the MEDLINE/PubMed and Web of Science electronic databases was carried out from March to October 2016. The learning curve is a graphical representation of the increase in learning from experience (repetitions). Thus, for example, an anxious state caused by behavior such as thinking about the future and the past, complaining, criticizing, judging and analyzing in excess, can be modified by training concentration (operant/action behavior), thereby reducing the excess of fast waves in the hindbrain (learned/reaction reflex behavior), leading the subject from the dysphoric state to a state of well-being.

Keywords: Behaviorism, learning curve, neurofeedback.

1. INTRODUCTION

1.1. Principle of Learning Curve

The learning curve is a graphical representation of increased learning (Y-axis) with experience (X-axis); it is literally a graphic record of the performance and self-control in any situation [1]. The first person to describe the learning curve was Hermann Ebbinghaus in 1885 [2, 3], in the field of psychology of learning, even though the name was not mentioned until 1909 [4]. Then, Theodore Paul Wright (1936) [1] drew attention to the subject when he published an article about aeronautical sciences, in particular on the reduction, over time, of the labor costs needed to construct an airplane. In other words, he described that the time to make the second plane was 80% of the time needed for the first, and the time to build the fourth plane was 80% of the time required to make the second plane [1].

Experts looking for a statistical pattern that could express the predictability of the curve reached the conclusion that, every time the number of repetitions is doubled, there is a fixed percentage reduction in the time needed to execute the task [5]. They also noted that shortening the time obtained by repeating the learning, usually ranges between 10% and 20% [1, 5]. Conventionally, learning curves are known in relation to these reduction rates, i.e., a curve of 80% presents 20% decreases in time each time the number of repetitions is doubled. A 90% learning curve has a 10% decrease in the execution time every time that the number of repetitions is doubled. Theoretically, a 100% curve does not present any improvement over time with the repetition of tasks [6].

As an example, if during a second session, a patient being trained with neurofeedback took 90 minutes in the frontal region of the 10-20 electrode placement system [7, 8] (F3, F4, F7, F8) to have over 95% of the amplitude of slow waves (2-11 Hz) below 35u using Peter Van Deusen's TQ-7 system [9], the time taken to drop below 40u in the first session was 100 minutes. Using the concept of a 90% learning curve and following the progression [6], we can infer that a training time of 81 minutes will be needed to get down

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to 30u in the 4th session, that is, 90% of the time spent on training in the 2nd session. The training time in the 8th session would be 72.9 minutes. That is, at each doubling of the accumulated production, the production time should be equal to the time of the previous session multiplied by the percentage of learning, in this example, 90% as illustrated in the table below [10].

Obtained result	Session	Training time
95% below 40u	1st	100 minutes
95% below 35u	2nd	90% of 100 = 90 minutes
95% below 30u	4th	90% of 90 = 81 minutes
95% below 25u	8th	90% of 81 = 72.9 minutes
95% below 20u	16th	90% of 72.9 = 65.6 minutes
95% below 15u	32nd	90% of 65.6 = 59 minutes

Considering the learning curve, the following algorithms can be used to calculate the times of tasks [10, 11].

$$Tn = T_1 \times n^b$$

Example: Time spent on 5th training session would be [10]:

$$T_5 = 100 \times \left(5^{ln0.9/ln2}\right) = 100 \times \left(5^{-0.105/0.693}\right) = 100 \times 0.784 = 78.4 minutes$$

$$T_n^* = T_1 + T_2 + T_3 ... + T_n$$

Another way of expressing the accumulated duration of the first n units, which can be used in scientific calculators, is the formula below [11]:

$$T_n^* = \sum_{i=1}^{n} \left[T_1 x i^{\frac{ln\%}{ln2}} \right]$$

Thus, the basis of neurofeedback training is to understand that you do not learn anything, such as math, reading comprehension, to play a musical instrument, languages, to change the reactions of your brain, etc. in one day [9]. Only one new synapse is created in one day, but for it to persist long term, it takes a lot of dedication and effort. If we compare this to the teachings of Piaget, to create a synapse would be assimilation and to make it remain long term and well defined in a specific neuronal network would be accommodation and the formation of a new permanent mental outlook [12, 13].

Any profession who repeats the same activity repeatedly creates more long-term synapses, freeing up the working memory, establishing knowledge, and increasing skills until achieving the best performance [14]. The more times a task is repeated, the better the professional or student becomes. With this, the job can be done faster and faster, until the highest level of dexterity is reached [15]. The repetition of certain activities leads, in itself, to an increase in efficiency [16]. The more complex, long and repetitive the task is, the more significant the learning curve is and its impact on productivity [1]. In the context of psychological approaches, repetition (part of conditioning) is one of the main tools of behaviorism [17].

2. BEHAVIORISM AND NEUROFEEDBACK

First, it seems relevant to clarify that, while most training is guided on the model of behavioral psychology founded by Ivan Petrovich Pavlov (1849-1936) [18, 19], Edward Lee Thorndike (1874-1949) [20], John Broadus Watson (1878-1958) [21], Burrhus Frederic Skinner (1904-1990) [22], Joseph Wolpe (1915-1997) [23], Albert Bandura (1925) [24, 25] and others, the use of brain training with neurofeedback is not a technique practiced just by psychologists. Every professional who intends to work with self-neuroregulation as a neurofeedback tool, whether trained in psychology, medicine, biomedicine, nutrition, physiotherapy, nursing, occupational therapy, education, dentistry, biology, physical education, administration, physics and engineering and others can use this instrument or resource [26].

In fact, neurofeedback is not an exclusive practice of any profession. The use of this instrument is free even though each profession has a different purpose [27]. Professions are created by law and the conditions, prerogatives, attributions and purpose of each profession are established by legal diploma. In Brazil, Article 47 in chapter VI of Decree 3688 of October 3, 1941 prohibits the illegal exercise of a profession, classifying this attitude as a contravention of the law [28, 29].

For example, if the neurofeedback coach is a psychologist and has the hypothesis that the client has a nutritional deficit, he or she is not permitted to prescribe a diet nor food supplementation, because this is the profession of a nutritionist [30]. Likewise, the nutritionist realizing that the patient's way of thinking interferes with the development of neurofeedback training, cannot do psychotherapy, because this is the work of a psychologist [31]. But both can work with the neurofeedback instrument without invading the prerogatives of the other profession [29].

The word 'train' comes from the Latin '*traginare*', meaning 'to pull or to drag' [32, 33]. This denotes sacrifice and at the same time, persistence, because of the dynamic act of repeatedly doing any human activity in society and in nature to achieve a high standard. This means that the individual must want to have the leading role in his actions during training, in other words, the greatest chance of success is when the patient studies about neurofeedback training in advance and looks for a trainer and not the opposite.

The act of repeatedly performing an activity makes conditioning possible. The word conditioning indicates a psychological process by which the definitive response is different from the natural or original response due to a stimulus, object or situation [34]. This term was initially only applied to reflex activities (responses directly related to survival of the organism), which were discovered by Pavlov and presented as conditioned reflexes [35, 36]. He noted that the individual can produce not only innate reflex responses, but also learned or conditioned reflex responses [37]. Thus, the discovery of reflex learning became known as classical conditioning [38]. Reflex behavior is solely a reaction, because it comes as a response of the autonomic nervous system (ANS). Pavlov discovered that it can be an inborn reflex or learned reflex; he proposed that only stimulation and response are analytical units [37]. In the case of neurofeedback, changes in brain wave pattern are clearly a learned reflex behavior, as the individual has no way to inhibit or increase a brain wave with a direct command. This change will only occur with the aid of visual or auditory feedback plus operant behaviors (action) to strive to concentrate.

Subsequently, Burrhus Frederic Skinner became the representative of the behavioral school by describing another form of behavioral learning called operant conditioning [39]. Operant behavior is an action and is defined by a triple contingency of stimulation, response and consequence, i.e. a consequence stimulates a change in behavior or models a different response [40].

When a consequence is able to change a behavior, it is called a reinforcer [41]; it is the consequence that makes a response effective [42]. Reinforcements can be positive [41] when they strengthen behavior with a good effect and negative when they strengthen the behavior by removing bad effects or aversive stimuli [43]. However, independently of whether the behavior change is a result of reflex or operant conditioning, both processes create new synapses and become long term if there is much commitment to training [44].

As behavioral learning is conscious, the work of behavioral learning involving neurofeedback assumes prior knowledge of the subject or theme, albeit superficial, similar to the proposal of cognitive behavioral therapy that works with psychoeducation [45, 46].

In the specific case of neurofeedback, there is a mixture of reflex behavioral learning [47] involving the manipulation of the autonomic nervous system, inhibiting or increasing the amplitude of the brain waves, and operant behavioral learning [48]. The patient plays the leading role in operant behavioral learning, because he instantly receives feedback as the amplitudes of his own brain waves are captured by an international 10-20 system of electroencephalography [8, 49, 50] and plotted using a Bioexplorer computer program with the images magnified by 1-4 channel amplifiers and projected as videos [9].

In addition to the images that can appear in the form of fractals, movies, cartoons or games, the patient can also control how he inhibits or strengthens specific brain waves using the sounds of a piano contained in a specific database of TRAINERS' QEEG in version 7 (TQ-7) of the system [9, 51]. The trainer can specify a target amplitude symbolized by a bar and the individual is trained to keep the brain waves below or above this target [9].

Before training with QEEG in TLC technique in neurofeedback with TQ-7 system [9], it is necessary to train in hemoencephalography (HEG) [52], specifically, near infrared hemoencephalography (NIR) [53]. Train in Fpz, F7 and F8. Fpz is the area of the brain responsible for planning, organization and motivation, F7 is the control area of verbal and behavioral impulses, speech and working memory, and F8 is the area responsible for emotional control and social skills. Together, these three areas form the prefrontal area responsible for concentration and attention [54].

Training with HEG and with correct diaphragmatic breathing [55] and cardiac variability [56], always preceding training with EEG, are essential to this proposal of cerebral learning as they enable most of the cerebral blood flow to go to this region thereby functioning as activating stimuli of neuron firing in this immense area of concentration through the process of cellular respiration [57].

3. FIRING OF NEURONS THROUGH CELLULAR RESPIRATION

The blood passes through arteries, arterioles, capillaries, and the cytosol, where glycolysis occurs, and then it proceeds to the mitochondria to the second stage of cellular respiration. This stage involves the conversion of energy sources: carbohydrates, proteins and lipids into just one molecule, adenosine triphosphate (ADP) by means of the Krebs cycle [58]. In the third stage, the respiratory chain, oxidative phosphorylation occurs and ATP [59] and exothermic energy are produced promoting neuron firing [60, 61].

Glucose is a molecule with six carbons. When glycolysis occurs, glucose is split forming two molecules of pyruvate or pyruvic acid with three carbons each [62]. For this to happen two molecules of ATP are consumed and by the end of glycolysis, four ATP molecules are produced [63]. Glycolysis has another role, the oxidation of the glucose molecule [64]. This process starts by using the energy-rich electrons of the glucose that are donated to a molecule called oxidized nicotinamide adenine dinucleotide (NAD^+). On accepting these electrons, NAD^+ is reduced (NADH) [65].

All the steps of glycolysis occur in the cytoplasm of cells with pyruvate entering into the so-called mitochondrial matrix [66]. On entering, it loses a carbon molecule, which is released as carbon dioxide, and pyruvate is transformed into acetyl [67]. This acetyl molecule is oxidized and its electrons passed to the NAD^+ molecule, reducing it to NADH. The acetyl binds to coenzyme A to form acetyl-CoA [68].

The acetyl-CoA enters into a cycle of reactions known as the Krebs cycle or citric acid cycle and the acetyl molecule is completely oxidized [69]. Its electrons are all removed and passed to the coenzyme carriers NAD and flavin adenine dinucleotide ($FADH_2$) [70], which carry the electrons to the last step, cellular respiration. At this stage, there is a release of two carbon dioxide molecules [71], that is, much of what we eat is expelled from the body in the form of carbon dioxide and so aerobic activities help you to lose weight [72]. More energy is needed for physical exercise with an increase in cellular respiration, i.e., sugars and fats are consumed producing carbon dioxide [73].

Glycolysis occurs in the cytoplasm of the cell [74], the Krebs cycle in the mitochondrial matrix and the respiratory chain in the inner mitochondrial membrane, that is, in the mitochondrial cristae [75]. NADH and $FADH_2$ arrive at this site and donate electrons, which are attracted to the oxygen and for this, pass through some proteins by means of the electron transport chain [76]. With this, proteins use the energy of these electrons to pump H^+ protons to the intermembrane space of the mitochondria where the electrons bind with oxygen to form water [76]. Electrons carried by NADH have higher charges than those carried by $FADH_2$ [77]. While NADH is capable of pumping three H^+ protons to the intermembrane space of the mitochondria, $FADH_2$ can only pump two H^+ protons [78]. The inside of the mitochondrial membrane is negatively charged, and so these protons are attracted back passing through another protein called ATP synthase, and each H^+ proton that enters this protein, causes it to rotate. As it rotates, it binds to an ADP group with one phosphate, thereby forming ATP [79]. Thus, 34 molecules of ATP are produced in the respiratory chain with a total of 38 molecules of ATP being produced in glycolysis and the Krebs cycle [79].

The TLC in neurofeedback of Peter Van Deusen with TQ-7 system, which is already in version 7.5 [9], currently has several training schemes called brain-trainer designs [80]. In one, referred to as the FRE2C design (2 channel), for example, used to increase or decrease the amplitudes of any frequency, there are adjustment mechanisms of the amplitudes of high, medium and low frequency waves in three columns. The first column from the left allows the 2-6 Hz, 2-9 Hz, 2-11 Hz or 2-38 Hz ranges to be reduced or increased. The middle column allows adjustments (reductions or increases) to the ranges: 13-38 Hz, 16-38 Hz, 19-38 Hz and 23-38 Hz and the right column allows adjustments to the 6-13 Hz, 9-13 Hz, 12-16 Hz and 13-21 Hz ranges [9].

If the trainer establishes a range of 20u for the 2-11 Hz range in two channels in the frontal area (F7 and F8) of the 10-20 system for example, each time the neurons fire below 20u, the patient will hear a high-pitched piano note. Moreover, if the trainer stipulates a target of 5u for the increased frequency of the 13-21 Hz range in the same F7 and F8 area, the subject who is being trained will hear a bass piano note every time the neurons fire above 5u [9]. Sound and images in the form of fractals or otherwise functioning as feedback linked to the active channels being trained are converted into nerve impulses by the thalamus and modulated by the superior and inferior colliculi in the metathalamus [81].

4. AUDITION PROCESS LINKED TO TRAINING IN NEUROFEEDBACK

The sound waves reach the external auditory canal and pass into the ear canal, where they are transmitted in limited frequencies. This pressure is reflected in the chain of ossicles, hammer, anvil and stirrup [82], causing pressure in the liquid medium (perilymph) of the scala vestibuli, coming to the helicotrema (hole that connects the scala tympani to the scala vestibuli close to the cochlear apex) and back to the scala tympani [83].

The sound pressure exerted on the ossicles is mediated by the tensor tympani and stapedius muscles [84]. Thus, the sound vibration is passed from the tympanic membrane to the oval window [85], which is a membrane region of the cochlea connected to the base of the stapes [86].

Consequently, the vibrations of the sound waves are transferred to the cochlear fluid [82]. The movement of this fluid (endolymph) vibrates the basilar membrane and the sensory cells [83]. The cilia of the hair cells, on lightly touching the tectorial membrane, generate nerve impulses, which are transmitted by the auditory nerve to the auditory center of the cerebral cortex [85].

The stereocilia of sensory cells are the site of mechanoelectric transduction, i.e., the processing of sound vibrations into nerve messages that can be interpreted by the brain [83]. The temporary deformation or deflection of the cilium towards the kinocilium opens cation channels allowing potassium (K^+) to enter, which depolarizes the hair cell [85].

The cation channels close before the cilium returns to its original position. Therefore, all training with neurofeedback should be performed using headphones [87]. Consequently, the patient only hears the piano notes from the computer database after achieving the target values stipulated by the trainer of reductions or increases in the amplitude of a particular brain wave [9, 88]. For this, the patient cannot be thinking but needs to be concentrated; the more the depolarization of hair cells occurs, the more notes the individual will hear due to transduction, and the more sound the individual hears, the more adequate the waves are [87, 88].

5. ANOTHER LOOK AT NEUROFEEDBACK: REFLEXION BY PETER VAN DEUSEN

It is a well-recognized tendency of the categorizing left hemisphere—and thus of professional literature in general—to see what it expects to see.

Neurofeedback is *ipso facto* categorized as an operant conditioning technique throughout the clinical literature, an opinion which leads to a whole set of expectations that actually channel research.

Psychologists were the developers and publishers of brain training rather than, for example, exercise physiologists. They categorized the process as behavioral, since that was in their frame of reference. Hence, investigation of neurofeedback has been largely limited to psychological literature on the behavioral end of the scale. It is no surprise that operant conditioning is the accepted model by fiat.

Operant conditioning (behavior controlled by consequences) is not a good fit for what happens in brain training. The “behavior” in brain training is the constantly shifting patterns of activation in specific pools of neurons. The “consequences” are beeps or points on a computer a few hours a week. The expected level of generalization would be very low.

Behaviorism deals with What I do, not Who I am or How I feel. It is about measurable actions, not states. However, brain training is rarely task-specific. Rather, it gives us a tool to adjust energy patterns in the physical brain.

That is what the EEG can show. That is what it can train.

Training can guide a brain toward more efficient operation, toward improved capacity to activate and maintain greater processing speeds, toward greater stability, improved ability to operate independently among its areas and structures, to link up for effective interaction when required and to enter and sustain a resting/ready awareness state. It is not about telling the organism what to do; it is about improving its capacity to do what it wishes.

If we move out of the realm of the Mind, there is an obvious correlation in training the other parts of our bodies to change capacity, control, ability to idle and activate. Physical training can improve energy production (aerobics), strength and tone (weights) and flexibility/coordination (yoga). The changes accrue over time with regular practice. Changes in the body’s energy system affect behavior by enabling it rather than controlling it.

Does it matter if we change our frame of reference? In this case, seeing brain training as exercise instead of conditioning changes the whole locus of control.

Someone submits me to conditioning. But, only I can exercise my body.

The provider trains my behavior. I change my capacities and habits.

6. KEY POINTS

Training of the brain with neurofeedback presents significant changes in the mental states of people who truly focus.

The training techniques during a neurofeedback session are based on behaviorism and are expressed in the learning curve.

The process of change involves operant behavior and learned reflex behavior linked to hearing, vision, cellular respiration and the autonomic nervous system.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

A CURVA DA APRENDIZAGEM DE PETER VAN DEUSEN EM NEUROFEEDBACK: ARTIGO DE REVISÃO

Resumo – O comportamento reflexo aprendido (Reação) de Ivan Pavlov (1849-1936) e o comportamento operante (Ação) de Burrhus Skinner (1904-1990) têm sido utilizados como abordagens técnicas numa perspectiva da curva da aprendizagem por meio de repetições em treinamentos com neurofeedback. O objetivo deste estudo foi descrever o significado e a aplicação dessas abordagens associadas e explicar suas implicações neurofisiológicas. Realizou-se uma revisão na base eletrônica MEDLINE/PubMed e Web of Science no período de março a outubro de 2016. A curva de aprendizagem é uma representação gráfica do aumento de aprendizagem com a experiência (repetições). Assim, por exemplo, um estado ansioso, ocasionado por comportamentos como: pensar no futuro e no passado, reclamar, criticar, julgar e analisar em excesso, pode ser modificado com treinamento da concentração (comportamento operante/ação), possibilitando uma redução do excesso de ondas rápidas na parte posterior do cérebro (comportamento reflexo aprendido/reação), conduzindo o sujeito do estado disfórico para o estado de bem-estar.

Palavras Chave – Behaviorismo, curva de aprendizagem, neurofeedback.

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