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A Neuroscience-Based Learning Technique: Framework and Application to STEM

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***Abstract*—**Existing learning techniques such as problem-based learning, project-based learning, or case study learning are learning techniques that focus mainly on technical details, but give no specific guidelines on learner's experience and emotional learning aspects such as arousal salience and valence, being emotional states important factors affecting engagement and retention. Some approaches involving emotion in educational settings, such as social and emotional learning, lack neuroscientific rigorousness and use of specific neurobiological mechanisms. On the other hand, neurobiology approaches lack educational applicability. And educational approaches mainly focus on cognitive aspects and disregard conditioning learning. First, authors start explaining the reasons why it is hard to learn thoughtfully, then they use the method of neurobiological mapping to track the main limbic system functions, such as the reward circuit, and its relations with perception, memories, motivations, sympathetic and parasympathetic reactions, and sensations, as well as the brain cortex. The authors conclude explaining the major finding: The mechanisms of nonconscious learning and the triggers that guarantee long-term memory potentiation. Afterward, the educational framework for practical application and the instructors' guidelines are established. An implementation example in engineering education is given, namely, the study of tuned-mass dampers for earthquake oscillations attenuation in skyscrapers. This work represents an original learning technique based on nonconscious learning mechanisms to enhance long-term memories that complement existing cognitive learning methods.

***Keywords*—**Emotion, emotion-enhanced memory, learning technique, STEM.

I. Introduction

IF thinking about a successful task-oriented educational method focusing on the development of sensory, motor and cognitive skills in childhood, this is the Montessori's method, which has been applied over 100, initially, with cognitive impairments. The Montessori method promotes freedom within limits and responsibility, it is based on empathy rather than direct instruction, providing with practice and sensorial materials to develop children's capabilities, and forming a new human being in a society of respect [1]. Montessori did not well develop further ideas for 12–18-year old education, since she thought they required a special education to address their needs [2]. Montessori teachers often feel fear or uncertainty about being able to apply Montessori's theories in new and innovative ways [3]. Non-Montessori practices such as real-life problems and project-based learning can also provide sensorial foundations and support the development of learner's motor skills and cognitive learning. Current advances in developmental cognitive neuroscience and recent neuroimaging technologies have the potential to make a positive contribution to this research and figure out the reasons why these methods work, so to focus then on the specific neurobiological mechanisms to better enhance learning.

The learning techniques such as problem-based learning, project-based learning or case study learning focus on the context, on technical analysis, and procedural implementation, but have no explicit concern on the learner's experience per se, do not mention specific guidelines related to the emotional arousal salience or valence that students experience to better engage and efficiently retain the information in vivid long-term memories. There have been attempts to involve emotions in educational settings, but those approaches are isolated from education, especially from higher education. One of the reasons may be the gap among cognitive psychology, neuroscience, pedagogy, and science, technology, engineering and mathematics (STEM) education which are dissociated disciplines. Even there are taboos between disciplines, like those in education focusing mainly on cognitive approaches, but disregarding behavioral learning. We can add other problems such as teaching uncertainty, lack of expertise or bravery to leave their comfort zone and dare to propose and implement new real-life projects in their classes. Therefore, the purpose of the present article is to identify the neurobiological mechanisms and connect them to build the learner's experience dimension, and scaffolding guidelines and tools, and settling the basis of a systematic framework of the neuroscience-based learning technique that could integrate different disciplines and identify the components of natural learning in terms of the brain's functions. Once this learning technique is proposed, authors indicate what the main problems in setting STEM projects for instructors are. Then, an example of STEM implementation in engineering education is presented, namely the study of a tuned-mass damper for a course of Dynamics; as well as the proposal of a learning frame.

In the following sections, the underlying neuroscientific principles are explained, as well as the guarantors of learning leading to long-term memory.

II. Neuroscience and the Routes to Emotional Memory

Neuroscience is a multidisciplinary and quickly developing field that looks at the structure and function of the human

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brain and nervous system, in such aspects as cellular and molecular biology, anatomy and physiology, human behavior and cognition, among other disciplines. Humans have about one hundred billion neurons, each with about thousand connections to other cells.

Emotion-Enhanced Memory (EEM) is the phenomenon when emotional stimuli are better remembered than neutral ones [4], where both stimuli's valence and arousal contribute to EEM via modulation of different mechanisms. EEM dependent on arousal is associated with automatic encoding processes [5]:

- EEM of negative arousing stimuli is mainly mediated by the amygdala-hippocampal network, which is associated with relatively automatic encoding processes. Threat-related stimuli may generate an early amplitude enhanced encoding on frontal sites, which might be processed unconsciously relative to happy and neutral stimuli [6].
- EEM of negative nonarousing stimuli is mainly mediated by a prefrontal cortex-hippocampal network, which is associated with controlled encoding processes.
- The amygdala is activated when processing positive low-arousing stimuli, and weakened as arousal increased for positive stimuli [7].

For other researchers, immediate EEM (memory tested immediately) dependent on arousal is not always associated with automatic processing:

- For positive valence stimuli was associated with controlled encoding processing.
- For negative valence stimuli was associated with automatic processing [8].
- For arousing stimuli in EEM, the amygdala plays a critical role, especially for negative arousing stimuli [9]. Both the amygdala and hippocampus proportionally activate when emotionally arousing stimuli are remembered [5]. But, memory for negative nonarousing stimuli is activated due to differential engagement of the prefrontal cortex [9].

EEM & immediate EEM dependent on valence was associated with controlled encoding processes [5], [8]. Immediately positive EEM was completely mediated by secondary-task performance (controlled attention) during encoding, but immediately negative EEM was not [10], [11].

III. The Mechanisms of Emotional Learning

The potential mechanisms by which the amygdala mediates the influence of emotional arousal on memories are [4]:

- Amygdala mediates conditioned emotional learning.
- It forms the Medial Temporal Lobe (MTL) Memory System in association with the hippocampus, entorhinal cortex, and perirhinal cortex. The MTL memory system is responsible for declarative memory, memory consolidation, contextual fear memory and complex conditioning which includes trace conditioning and conditional discrimination learning.
- The amygdala and the sensory neocortex directly relate each other to mediate memory storage, as well as conceptual and perceptual priming.
- The amygdala and the cerebellum indirectly relate each other to mediate reflexive conditioning and motor learning.

In the case of neurohormonal memory modulation: The amygdala directly triggers the release of stress hormones through the subcortical Hypothalamic–Pituitary–Adrenal axis (HPA), in turn, feedbacking onto all the previous four systems to mediate long-term memory consolidation and storage. The amygdala and the subcortical striatum semi-directly relate each other to mediate procedural (habit) learning and reward learning. The amygdala semi-directly relates with both dorsal and ventral prefrontal cortex to mediate short-term working memory, and higher-order declarative memories. The amygdala and the ventral prefrontal cortex mediate semantic memory, conceptual priming, autobiographical retrieval, and extinction learning. The amygdala and the dorsal prefrontal cortex mediate working memory, meta memory, memory strategies, and prospective memory. Therefore, the amygdala is a key human alarm sensor that triggers emotional learning. The higher the arousal and valence levels from the stimuli, the stronger the memories associated to the events.

There are four main features of an event that trigger stress hormones such as adrenaline, noradrenaline and cortisol. These features are novelty, unpredictability, threat to ego, and sense of low control [12]. These hormones arrive at the brain after an emotional event and modulate long-term memories. A stressful experience causes specific emotions, and a particular emotion does not always elicit a stress reaction. Emotions and stressors may generate bodily reactions, and both may increase arousal. Emotions are induced by emotional situations, whereas stress is usually induced by a social situation. Besides these four stressors, avoidance and reward are also added as additional factors that create highly arousing and pleasant situations. Novelty, unpredictability, threat to ego, sense of low control, avoidance and reward are called by the authors as the N.U.S.T.A.R. factors that trigger emotional learning.

Learning can be significantly enhanced by nonconscious learning. Emotional learning is enabled by powerful chemicals. Chronic stress is bad, but acute stress is a natural mechanism for alertness. Instructor has a very responsible and ethical role in learning. Therefore, instructors are encouraged to learn these brain mechanisms in order to find an optimal and acceptable level of arousal & valence for an efficient learning process to get long-term emotional memories.

IV. Framework and STEM Application

The framework for Neuroscience-based Learning (NBL) consists of three parts: 1) Planning, 2) Scaffolding, and 3) Monitoring and Feedback.

The Planning stage is based on the backward design concept. It consists of three parts: 1) the course outcomes, where the learning outcomes, program outcomes and soft skills competences to be strengthened are set. 2) The real-life problem to be analyzed by students, the active learning method for delivery, and the project activity duration. 3) The planning description of the main project challenges.

The Scaffolding stage consists of project instructions that

are concisely written with complete and self-content information addressed to students in order to carry out the weekly project activity. It contains a short technical description of concepts, methods, measurements, etc. as well as the specific number of deliverables, templates and presentation requirements, way of delivery, and due dates.

The Monitoring and Feedback stage consists of the instructor's notes and remarks in a fashion of keeping note of what worked best, and what should be changed next time. It is about the creation of "The Best Practices" while supervising the on-going work, and when the "Just-in-Time Support" was provided by the instructor to adjust and help students when it was required. This stage also includes the activity evaluation for the instructor to assess the efficiency of the process. This frame is now applied for a project in the course "Engineering Mechanics: Dynamics" for both third-semester civil and mechanical engineers at MEF University. This course is delivered in two sections for a total of 58 students. The project is called: "Study of a Tuned Mass Damper for Attenuating Oscillations", and the objectives of the project are:

- Develop a project to learn an advanced engineering topic (Tuned-Mass Damper) through a real-life situation by analyzing the seismic effect on tall buildings.
- Develop creativity & critical thinking skills by a Do-It-Yourself activity at home conditions: Design & construction of the physical prototype of a building-like structure with minimal specifications and supervision.
- Stabilize the structure by trial & error tuning (due to lack of background) of a damper from an initial condition of displacement.
- Apply a pixel-tracking freeware to measure and graph decaying oscillations.
- Learn how to apply approximations in engineering life.
- Use the logarithmic decrement method to calculate basic vibration parameters for a cantilever beam with damped beam and end masses, modeled as a single-degree-of-freedom system.
- Compete for the maximum efficiency of attenuation.
- Develop time management, teamwork, and report writing.
- Accomplish the project in the shortest extra-class time, so to not disturb with midterms by using home-do-it-yourself.

This specific project introduces technical concepts such as multi-degree-of-freedom problems converted into a single degree of freedom, such as the behavior of a vertical single-mass cantilever beam. As well as engineering concepts: forced, unforced, overdamped, critically damped, undamped, underdamped vibrations; mass, spring, viscous-friction, damper; degrees of freedom (DOF), multiple-DOF system, conversion into a single DOF; solution of complex optimization problems by trial & error; initial conditions; engineering approximations; and logarithmic decrement method.

The NBL framework is now presented for this project.

A. Planning Stage

1. Course Outcomes

- Learning outcomes (LO): Vibrations
- Program outcomes (PO): Design; solve complex problems; recognition of professional responsibilities, judgments, hypothesis generation, and evaluation of impact; experimentation; life-long learning
- Soft skills (SS), competences: Reflection, creativity, resourcefulness, critical thinking, inquiry, teamwork, self-learning, self-confidence, self-efficacy, endurance, grit.

2. The Real-Life Problem: Reduce Earthquake Oscillations in A Skyscraper

- Active learning method for delivery (match with PO): Project-oriented learning (POL) as home-do-it-yourself project, field study, judgments, experimentation, and life-long learning.
- Project activity duration: The whole project lasts four weeks, and consists of the following stages:
  - Stage 1. Construction of building-like frame (week 1)
  - Stage 2. Design of the tuned mass damper (week 2)
  - Stage 3. Final damper tuning and tracking the motion of a point within the frame (week 3)
  - Stage 4. Calculations, report and presentation video (week 4)

3. Planning Description of One of the Main Project Challenges: Learning How to Use a Measurement Software

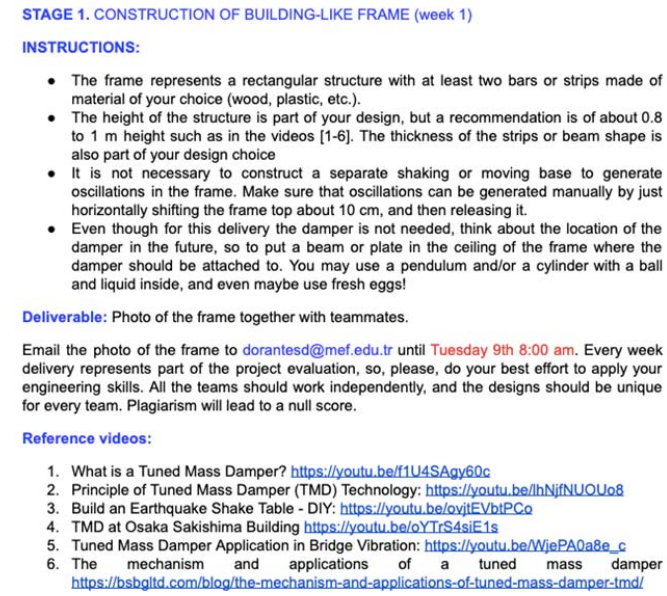
- Novelty (match with potential SS): "Earthquake oscillations can be stopped?" (reflection); "I will build a device that stops earthquake effects! (reflection); Motion can be measured by a contactless method by video processing!! (reflection)
- Unpredictability (match with potential SS): Students did not expect they need to install and learn the Tracker software by themselves (resourcefulness, self-learning, self-confidence).
- Threat (to Ego) (match with potential SS): "Am I capable of doing this task?" (self-confidence).
- Sense of Low Control (match with potential SS): "I don't know how to do that?" (self-confidence).
- Avoidance (match with potential SS): "I don't want to lose points!" (endurance/grit).
- Reward (match with potential SS): "I love extra points!" (seeking).

B. Scaffolding

A sample of instruction for the first week (stage 1) is shown.

C. Monitoring and Feedback Stage

The monitoring and feedback stage consists of the instructor's notes and remarks in order to create "The Best Practices" while supervising the on-going work. It also notes when the "Just-in-Time Support" was provided to students.



STAGE 1. CONSTRUCTION OF BUILDING-LIKE FRAME (week 1)

INSTRUCTIONS:

- The frame represents a rectangular structure with at least two bars or strips made of material of your choice (wood, plastic, etc.).
- The height of the structure is part of your design, but a recommendation is of about 0.8 to 1 m height such as in the videos [1-6]. The thickness of the strips or beam shape is also part of your design choice
- It is not necessary to construct a separate shaking or moving base to generate oscillations in the frame. Make sure that oscillations can be generated manually by just horizontally shifting the frame top about 10 cm, and then releasing it.
- Even though for this delivery the damper is not needed, think about the location of the damper in the future, so to put a beam or plate in the ceiling of the frame where the damper should be attached to. You may use a pendulum and/or a cylinder with a ball and liquid inside, and even maybe use fresh eggs!

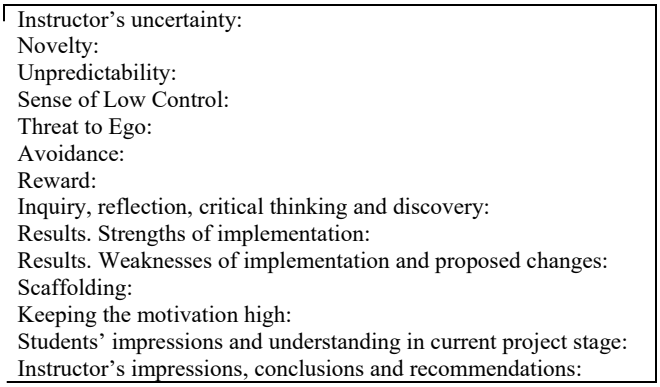
Deliverable: Photo of the frame together with teammates.

Email the photo of the frame to dorantesd@mef.edu.tr until Tuesday 9th 8:00 am. Every week delivery represents part of the project evaluation, so, please, do your best effort to apply your engineering skills. All the teams should work independently, and the designs should be unique for every team. Plagiarism will lead to a null score.

Reference videos:

1. What is a Tuned Mass Damper? https://youtu.be/f1U4SAgy60c
2. Principle of Tuned Mass Damper (TMD) Technology: https://youtu.be/IhNjfNUOUo8
3. Build an Earthquake Shake Table - DIY: https://youtu.be/ovjtEVbtPCo
4. TMD at Osaka Sakishima Building https://youtu.be/oYTrS4siE1s
5. Tuned Mass Damper Application in Bridge Vibration: https://youtu.be/WjePA0a8e_c
6. The mechanism and applications of a tuned mass damper https://bsbgltd.com/blog/the-mechanism-and-applications-of-tuned-mass-damper-tmd/

Fig. 1 Example of stage-1 instructions for students



Instructor's uncertainty:
Novelty:
Unpredictability:
Sense of Low Control:
Threat to Ego:
Avoidance:
Reward:
Inquiry, reflection, critical thinking and discovery:
Results. Strengths of implementation:
Results. Weaknesses of implementation and proposed changes:
Scaffolding:
Keeping the motivation high:
Students' impressions and understanding in current project stage:
Instructor's impressions, conclusions and recommendations:

Fig. 2 Example of Monitoring and Feedback stage notes

This project was successfully accomplished in four weeks, while sustaining student motivation and enthusiasm, as well as developing creativity, and critical thinking. The project successfully sparked interest in engineering, and the change in the teaching practice was worthwhile. Even though the project is an advanced topic usually taught in senior or elective courses of bachelor and master's programs, the project was easy enough designed and can be recommended even in high-school levels.

V. Conclusion

When human beings get emotional, the amygdala, the reward circuit and the neocortex mediate emotional learning resulting in vivid, long-term memories. Learning can be significantly enhanced by nonconscious learning. Emotional learning is enabled by powerful chemicals. Therefore, instructors have a very responsible and ethical role in learning. Instructors are encouraged to learn the neuroscientific mechanisms in order to find an optimal and acceptable level of arousal & valence for an efficient learning process leading to long-term memories.

The NBL technique was for the first time introduced with the help of a framework that facilitates its application in STEM projects. However, NBL can be applied to any other discipline and type of learning activity. NBL states that novelty, unpredictability, threat to ego, sense of low control, avoidance and reward (N.U.S.T.A.R.) are the main factors that trigger emotional learning. A project on the study of a tuned mass damper for attenuating oscillations was described as a successful NBL application example.

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