Virtual reality adaptive stimulation of limbic networks in the mental readiness training

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Abstract. A significant proportion of severe psychological problems in recent large-scale peacekeeping operations underscores the importance of effective methods for strengthening the stress resilience. Virtual reality (VR) adaptive stimulation, based on the estimation of the participant’s emotional state from physiological signals, may enhance the mental readiness training (MRT). Understanding neurobiological mechanisms by which the MRT based on VR adaptive stimulation can affect the resilience to stress is important for practical application in the stress resilience management. After the delivery of a traumatic audio-visual stimulus in the VR, the cascade of events occurs in the brain, which evokes various physiological manifestations. In addition to the “limbic” emotional and visceral brain circuitry, other large-scale sensory, cognitive, and memory brain networks participate with less known impact in this physiological response. The MRT based on VR adaptive stimulation may strengthen the stress resilience through targeted brain-body interactions. Integrated interdisciplinary efforts, which would integrate the brain imaging and the proposed approach, may contribute to clarifying the neurobiological foundation of the resilience to stress.

Keywords. virtual reality adaptive stimulation, limbic networks, mental readiness training, stress resilience, physiological measurements, emotional state estimation

Introduction

A significant proportion of severe psychological problems in recent large-scale peacekeeping operations [1] highlights the significance of the resilience to stress. The mental readiness training (MRT) [2] as a modification of the stress inoculation training (SIT) [3] for military personnel, has been proposed as a stress resilience building approach. In comparison with the SIT, the MRT places a lesser emphasis on lectures concerning stress, but a greater emphasis on the practice of stress-coping skills in the context of a relevant military training. According to [4], an individual’s stress resilience includes both an ability to retain a quality task performance under highly

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stressful conditions (stress resistance), as well as an ability to regain the normal functioning after the exposure to such stressful conditions (stress recovery). The MRT based on VR adaptive stimulation may contribute to both aspects of stress resilience, but each aspect should be analyzed separately from the perspective of underlying neural mechanisms. While changes in the brain-body interaction influenced by MRT based on VR adaptive stimulation result in physiological fluctuations, a further analysis is needed with respect to a direct relevance of these processes to stress resistance and stress recovery. Existing correlates of psychotherapy treatment outcomes visible in “limbic” and “paralimbic” brain structures [5,6] suggest that neurobiological considerations of stress resilience may strengthen practical applications of the MRT.

1. Physiology-Driven Adaptive Virtual Reality Stimulation for MRT

Following the promising applications of virtual reality (VR) in psychotherapy of stress-related disorders and SIT [7], the concept of physiology-driven adaptive VR stimulation [8] is proposed as potentially useful adjunct to the MRT. The concept involves delivery of audio-visual stimuli in a closed loop, based on the information about the participant’s emotional state, which is extracted from physiological measurements by the neural network based emotional state estimator [9]. This approach may facilitate personalized elicitation and monitoring of potential psychophysiological correlates of the stress resilience, using the stimuli with desired semantics and emotional properties. Various control laws may be implemented in physiology-driven adaptive VR stimulation, to accomplish the goals of a specific stimulation strategy. Regardless of the control law, the control vector $u_k = u(kT)$ sent to the stimuli generator, where $T$ is a basic time step and $k \in \mathbb{N}_0$, may be represented as:

$$u_k = (\text{stimType}_k, \text{discreteEmo}_k, \text{valence}_k, \text{arousal}_k, \text{semantics}_k),$$

where $\text{stimType}_k \in \text{StimuliTypes} = \{\text{IMAGE}, \text{SOUND}, \text{VIDEO}, \text{VR}, \ldots\}$ denotes a type of the stimulus to be generated, $\text{discreteEmo}_k \in \text{DiscreteEmotionSpace} = \{\text{JOY}, \text{SADNESS}, \text{FEAR}, \text{ANGER}, \text{DISGUST}, \ldots\}$ stands for a discrete emotion to be elicited by the stimulus, $(\text{valence}_k, \text{arousal}_k) \in \text{DimensionalEmotionSpace} = [1.0, 9.0] \times [1.0, 9.0]$ represents a dimensional valence/arousal description of the emotion, and $\text{semantics}_k \in \text{SemanticsSpace}$ is the description of the content of the stimulus (e.g. by a well-formed propositional formula consisting of keywords and logical and, or, not operators). For example, the following control vectors would potentially yield a rather extreme change of the participant’s emotional state after step $n$, with $m < n$:

$$u_m = (\text{IMAGE}, \text{SERENITY}, 8.0, 2.0, \text{flower or sunset}),$$  

$$u_n = (\text{VIDEO}, \text{DISGUST}, 2.0, 8.0, \text{mutilation}).$$

After the control vector $u_k$ has been formed and sent to the stimuli generator, the stimulus that best matches $u_k$ is found and delivered to the participant. The cascade of events triggered by the stimulus in the participant’s brain produces physiological manifestations that are processed by the emotional state estimator. The estimator outputs enter the controller, vector $u_{k+1}$ is generated, and the process continues.

2. The Neurobiology of Emotions

Complex sensory-cognitive-emotional-executive interactions between the brain and the body can be described by the “high road” and “low road” neuronal circuits [10], which
connect both “limbic” and “paralimbic” cortices. These interactions give rise to the subjective and physiological components of emotion (Figure 1). Upon delivery of an audio-visual stimulus, the information from sensory organs travels to the thalamus (Th). The thalamus acts as a relay station, forwarding sensory information along the “high road” pathways to appropriate primary and secondary association auditory (Aud I, II) and visual (Vis I, II) cortices for further processing. The multimodal integration of this information is performed in the highest-level association cortex in parietal-temporal-occipital region (PTOAssoc) [11], as well as in another highest-level association cortex, i.e. inferior temporal cortex (ITAAssoc), related to long-term declarative memories (e.g. [12]). This information is made accessible to the prefrontal association cortex (OFC/VMPFC and DLPFC), which is bidirectionally connected with the amygdala (Am). The amygdala is regarded as an important structure for the emotional memory, which has been experimentally tested especially in relation to the emotion of fear [10]. The “top-down” regulation of emotions by orbitofrontal and ventromedial components of the prefrontal cortex (OFC/VMPFC) is particularly important, as it involves an integration of cognitive information loop, i.e. parietal-dorsolateral prefrontal cortex (PTOAssoc-DLPFC), long-term memories via the hippocampus (Hc), the fear via the amygdala, and executive functions via the DLPFC and the premotor cortex (PMC).

Figure 1. Pathways of the subjective and physiological components of emotion
The “low road” circuit simultaneously transmits the audio-visual sensory information directly from the thalamus to the amygdala, where it is assessed with respect to its relevance for the organism (e.g. [13]). The information along the “low road” circuit arrives to the amygdala faster than through the “high road” circuit. This is particularly important when the stimulus is relevant for the survival of the organism. In such situations, emotional reactions will be elicited even before the stimulus has been fully processed. The net result is an “immediate” protective reaction against the fatal threat, but false alarms may also occur due to the presence of unprocessed stimuli.

Amygdala projections to the hypothalamus (Ht), which further projects to brainstem structures such as the lateral reticular formation (LatRF), lead to changes in the activity of autonomic nervous system and viscera [14]. These “low road” brain-to-body pathways produce changes in skin conductance, the heart rate, the respiration rate etc., which can be measured by physiological acquisition devices. Concurrently with changes in the autonomic nervous system, the hypothalamic-pituitary-adrenal axis regulates the amount of glucocorticoids and other hormones, which prepare the organism to cope with the current situation. Other possible manifestations may involve the emotional behavior, which relies on appropriate connections of “limbic” structures with motor circuitry.

The subjective experience of emotion, i.e. the feeling, arises as a result of the activity of body-to-brain pathways, through which visceral changes are sensed by the brain, and brain pathways that represent these changes together with the eliciting stimulus or situation [15]. Principal representational structures involved with feelings are thought to be visceral sensory nuclei in the brainstem (ViscSens), insular cortex (In) and primary and secondary somatosensory cortices (SomSens I, II) [15].

The prefrontal cortex, which is considered as an essential part of the frontolimbic system [16], displays the greatest sensitivity to the harmful effects of the exposure to stress [17]. Various parts of “paralimbic” and “limbic” cortices are known to be affected in stress-related disorders as well [5].

3. Neurobiological Considerations of the Stress Resilience

Very stressful, dangerous tasks are expected to induce a strong activation of the amygdala, which can adversely affect the stress resilience, i.e. both the stress resistance and stress recovery. For the stress resistance, the relevant neurobiological aspect is related to amygdala projections to the DLPFC, which is responsible [17] for working memory and the attentional set. These projections enable the amygdala activity to interfere with mission-related cognitive processes that rely on working memory and require sustained attention. Therefore, an approach to improving the stress resistance involves over-learning of the basic operational skills and standard operating procedures, so that they can be performed “automatically”, without requiring attention. In stressful situations that demand highly cognitive abilities, the inhibition of the amygdala activity by the OFC/VMPFC may play an important role in the successful performance of stressful tasks. Based on contextual information provided by the hippocampus, the OFC/VMPFC is able to perform a selective context-dependent amygdala inhibition. Inhibitory connections from the OFC/VMPFC to the amygdala may be strengthened during the stressful training by practicing the stress-coping skills that are an integral part of MRT. A stronger inhibition of the amygdala should lead to a decreased activation of the hypothalamus and the brainstem nuclei. Therefore, one would expect
to observe lowering of the physiological reactivity to stressful stimuli with improvement in the stress-coping skills. Changes in the physiological reactivity of an individual during delivery of various stressful stimuli can be longitudinally monitored by the physiology-driven adaptive VR stimulation. Stressful stimuli can also be delivered through various other forms of training, but the physiological monitoring may be more challenging if the training involves vigorous movements.

For the stress recovery, i.e. the prevention of stress-related disorders, an approach applying the physiology-driven adaptive VR stimulation presented in [8] resembles the approach from the previous paragraph. However, it may also be important to prevent a post-traumatic generalization of a specific traumatic event to a much broader, and only marginally related, innocuous context. Due to the heightened amygdala activity during the traumatic event, the neural representation of the critical aspects of the trauma is expected to consolidate quickly into long-term memory (ITAssoc). As biochemical synaptic reinforcement process is thought to underlie memory consolidation [18], it is important to block this process on synapses between the neural representation of the critical aspects of the traumatic event and the neural representation of the innocuous context. Thus, obstructing the simultaneous rehearsal of the critical aspects and the innocuous context of the trauma may be helpful in an effort to prevent strengthening of synapses between the corresponding neural representations. As memory consolidation is believed [18] to continue during the weeks after the traumatic event, a potential approach in this period may be overloading the trauma survivor’s working memory with episodes of personal relevance that have a contrasting motivational basis. Another compatible approach may involve incorporating the elements of the innocuous context into nontargeting real-life, virtual or iconic scenarios. This approach should facilitate storage of the innocuous context with strengthened nontargeting associations and weakened associations to the critical aspects of the traumatic event. Physiology-driven adaptive VR stimulation might be helpful in this regard, when applied by an expert. The role of the expert would include choosing the stimuli that approximate innocuous context of the trauma, and then conducting the conversation to engage the trauma survivor into plausible nontargeting situations related to the presented stimuli. Therefore, a semantically driven choice of stimuli based on the data gathered from an interview with the trauma survivor would be indicated in preference to the physiology-driven search of the stimuli database. Physiological measurements would remain useful for gauging the strength and breadth of associations between the critical aspects and the innocuous context of the traumatic event. Holmes and colleagues [19] have proposed and tested another related approach that targets the memory consolidation of traumatic flashbacks.

4. Conclusion

The inhibition of the amygdala response by the prefrontal cortex can be strengthened by the MRT based on VR adaptive stimulation. This approach may significantly increase the stress resistance of trainees, in combination with a real-life exercise and training. The stress recovery may be facilitated by an immediate post-trauma VR adaptive stimulation during the process of consolidation of the traumatic event memory. The immediate post-trauma stimulation strategy, via nontargeting scenarios that focus on the innocuous context of the individual’s traumatic experience, may prevent broad associations with the traumatic event. An interdisciplinary approach to the stress
resilience is called for, which would integrate the brain imaging, the MRT based on VR adaptive stimulation, and the psychological stress resilience research.

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