Physiology-Driven Adaptive Virtual Reality Stimulation for Prevention and Treatment of Stress Related Disorders


Abstract

The significant proportion of severe psychological problems related to intensive stress in recent large peacekeeping operations underscores the importance of effective methods for strengthening the prevention and treatment of stress-related disorders. Adaptive control of virtual reality (VR) stimulation presented in this work, based on estimation of the person’s emotional state from physiological signals, may enhance existing stress inoculation training (SIT). Physiology-driven adaptive VR stimulation can tailor the progress of stressful stimuli delivery to the physiological characteristics of each individual, which is indicated for improvement in stress resistance. Following an overview of physiology-driven adaptive VR stimulation, its major functional subsystems are described in more detail. A specific algorithm of stimuli delivery applicable to SIT is outlined.

Introduction

Large peacekeeping operations including hundreds of thousands of deployed soldiers, with some 10% to 50% of combat-related injuries being psychological, emphasize the responsibility of international organizations to provide extraordinary mental care for their personnel. Social and political damages of posttraumatic stress disorder (PTSD) and major depression in the recent peacekeeping operations are estimated to range in billions of dollars. The consequences of untreated or inadequately treated PTSD and depression are far-reaching, affecting individuals and their families, as well as society in general, in the form of marital problems, domestic violence, unemployment, homelessness, drug and alcohol abuse, suicides, and similar behaviors.

Mental readiness training, which builds on stress inoculation training (SIT), is one aspect of the needed mental care, which is focused on making individuals more resilient to adverse psychological effects of combat. On the other end of the spectrum, a variety of therapeutic approaches exists for healing individuals who already suffer from combat-related psychological disorders.

As virtual reality (VR) applications are growing in psychotherapy, VR and psychophysiological measurements have been tested and applied in treatment of adverse psychological consequences of combat, like PTSD, and also in SIT for military personnel. Such applications of VR and psychophysiological measurements may be further enhanced by physiology-driven adaptive VR stimulation.

Specifically, in VR exposure therapy, the therapist operates a user interface to deliver gradually to the patient the virtual stimuli of anxiety-provoking situations. Use of VR for PTSD treatment has been tested with promising results in Vietnam War veterans, survivors of the World Trade Center attack, soldiers from Afghanistan and Iraq operations, road accident survivors, victims of physical aggression, and others. Physiology-driven adaptive VR stimulation attempts to optimize and customize the therapy by relieving the therapist of repetitive interface manipulation and monitoring of the patient’s physiology. In this approach, the therapist’s assessment of the patient’s emotional state is complemented by an automated assessment based on continual interpretation of multiple physiological signals and adjusted by the subjective ratings that the patients may intermittently provide during the session. Further, the decision support provided by the proposed adaptive closed loop based on the current emotional state estimation can alleviate the therapist’s involvement in the user interface manipulation. With such additional assistance, therapists can increase their focus on the treatment and conduct more comprehensive therapy.

As SIT shares certain similarities with exposure therapy, like exposure to stressful experiences delivered in a gradual manner, the physiology-driven adaptive VR stimulation might be applicable to SIT in high-stress occupations like military. SIT is a cognitive-behavioral intervention that has been applied for preventive and treatment purposes in various contexts. It is conducted through the following three overlapping phases: initial, conceptualization phase, focused psychiatric evaluation phase, and treatment phase.
on development of collaborative relationship between the trainee and the trainer, also including stress education; skill acquisition and rehearsal phase, in which the trainees are taught stress-coping skills and acquire these skills through repeated practice; and a final phase in which trainees apply the acquired stress-coping skills over a sequence of increasingly intense stressful experiences relevant to their real-life situation.3 The third phase of SIT may be accentuated within the military context; Thompson and McCreary1 point out the need to reduce lectures concerning stress and to focus on message and technique delivery that is directly integrated into more intense training situations with operational relevance. A recent review finds several studies in which VR technology is used in SIT for military personnel.6 The reviewed studies show that training in VR, with versus without stressors, may result in better performance during testing and that application of the stress-coping skills may lower the experienced stress during VR training. The review also mentions evidence that SIT may provide protection from stress-related psychological disorders. In an investigation regarding the protocol of stressor delivery during training for task performance in stressful situations, temporally separating task training from stressor exposure has exhibited comparable or superior effects to the combined training.17 As the existing VR-SIT studies in the military context seem to use combined training in the third phase of SIT, the physiology-driven adaptive VR stimulation for SIT is focused exclusively on experiencing the stressors for the purpose of increasing resistance to stress-related psychological disorders.

Our work starts with the description of the generic concept of physiology-driven adaptive VR stimulation. Intended applications of this concept are SIT and PTSD exposure therapy for high-stress professional groups, like military personnel. We then describe the three major functional subsystems of the concept: generation of multimedia stimuli, estimation of the emotional states from physiology, and closed-loop control of stimuli according to the emotional state. Finally, the SIT-specific algorithm for personalized stimuli delivery based on the individual’s emotional state is presented.

Physiology-Driven Adaptive VR Stimulation

The broad idea of adaptive systems using physiology in a feedback loop has been around since the biocybernetics program in the 1970s.18 More recent examples of adaptation of computer systems based on emotion of their users, where physiology is used as an emotion indicator, may be found in the affective computing field.19 One of the visions of this field is endowing computers with automated emotion recognition capabilities in order to facilitate a range of applications in which the computers respond appropriately to the emotions of their users.

Physiology-driven adaptive VR stimulation targets applications in which influencing the person’s emotional state in a controlled manner is conducted by display of stimuli in various media forms, like static pictures, sounds, and synthetic virtual stimuli combined with real-life video clips. To this end, the physiology-driven adaptive VR stimulation concept includes time-synchronized stimuli generation, acquisition of the person’s physiological response, person’s emotional state estimation, and adaptive closed-loop control that leads to subsequent generation of new stimuli. This concept has been discussed in the context of VR exposure therapy for PTSD7 and subsequently outlined in the context of SIT.20 Generally, specific applications like these may be derived from the concept by specifying the actual control strategy, appropriate stimuli generation, and emotional state estimation in line with the requirements of a particular application. Participant–supervisor terminology is employed when referring to the human users in generic discussion of the concept, replacing patient–therapist or trainee–trainer rhetoric of exposure therapy or SIT respectively.

Physiology-driven adaptive VR stimulation is decomposed into four logical subsystems (Fig. 1). The stimuli generator

FIG. 1. Four logical subsystems of physiology-driven adaptive VR stimulation.
receives control signals $u(t)$ from the adaptive controller and generates the corresponding stimuli. Control signals may specify the semantics and/or emotional properties of the stimuli together with the desired media forms. Control signals, using the unique index of each stimulus in the stimuli database, may also directly specify the stimuli that need to be generated. This capability is added to ensure compatibility with VR exposure therapy systems, where such control signals are commonly generated manually by the supervisor.

The emotional state estimator receives various physiological signals $P(t)$ of the participant and estimates his or her emotional state. Estimated emotional state may be represented in line with the dimensional model of emotions,\(^{21}\) that is, as numeric values along valence (unpleasant–pleasant) and arousal (calm–aroused) axes, $v(t), a(t)$. Generally, participants may also occasionally rate their emotional state in valence/arousal terms. This information enters the emotional state estimator to be used if needed, since the emotional state encompasses subjective/experiential and also behavioral and cognitive components in addition to physiology.\(^{22}\) However, behavioral and cognitive interpretation is a significant challenge for technology relative to humans, requiring further focused research in automated emotion recognition from voice, speech, facial expressions, logical cognitive tests, and so on. During estimation, the emotional state estimator computes various needed physiological features. Physiological signals and features that may be visualized to the supervisor are forwarded as vector $PF(t)$ to the adaptive controller.

The adaptive controller is a focal point where all diverse information is collected: participant’s valence/arousal ratings $v_r(t), a_r(t)$, physiological signals and features, $PF(t)$, estimated emotional state, $v(t), a(t)$, as well as the information $u_r(t)$ regarding the annotation of the generated stimuli, which is generally different from the control signal $u(t)$. The rationale is that the adaptive controller holds the decision-making logic regarding the best stimuli to deliver based on the participant’s estimated emotional state. In order to make the best decision, it needs all the available information that may be potentially relevant for decision making.

For these reasons, the adaptive controller is also the most appropriate subsystem for storing this information permanently into the Subject’s Aggregated Knowledge Database (SAKD). Information in the SAKD can be subsequently used by the adaptive controller, in the same session or later sessions. In particular, the internal state of the adaptive controller at the end of each session can be stored in the SAKD in order to be reloaded at the beginning of the next session. Information in the SAKD may also be used in offline analyses by humans for research into further improvements to the decision-making engine of the adaptive controller.

The Reference Knowledge Database (RKD) is based on relevant data from literature and/or on integrated SAKDs of previous participants. The adaptive controller is expected to use the RKD in the beginning of the first session if it needs to make an educated guess regarding the participant’s characteristics when no other information is yet available. The RKD may also be useful in any decision making that needs to compare the individual participant’s characteristics to the characteristics of a wider population.

The adaptive controller in some applications may be expected to collaborate closely with the supervisor during the session. This may be particularly pronounced in VR exposure therapy for PTSD,\(^{7,8}\) as the patients may be very sensitive to the potential mistakes by the adaptive controller. In such applications, the adaptive controller should by design have its decision making subordinate to the supervisor’s authority (manifested as control signal $u_{sup}(t)$ emanating from the supervisor’s graphical interface). The adaptive controller also needs to supply the supervisor with information useful for making the most appropriate decisions. In this regard, the adaptive controller may also be considered a type of an adaptive advisor, an intelligent goal-based agent that through iterative corrective process offers a list of optimal stimuli to the supervising human expert.

### Stimuli Generator

Within the physiology-driven adaptive VR stimulation, the stimuli generator is responsible for finding the best-matching stimuli from its databases with respect to the semantics, emotional properties, and media form specified by control signals from the adaptive controller. In this process, it is important that the signals result in emotionally and semantically aligned stimuli, which are individually conformed to a specific participant’s mental state.

The stimuli generator uses emotionally and semantically annotated stimuli databases. International Affective Picture System (IAPS)\(^{23}\) and International Affective Digitized Sounds (IADS)\(^{24}\) are examples of such publicly available databases of static pictures and sounds. Emotional annotations of IAPS and IADS stimuli include valence and arousal values, ranging from 1.00 through 9.00, that represent maximum unpleasantness through maximum pleasantness and maximum calmness through maximum arousal respectively. These databases also use free-text keywords, or tags, to describe the semantics of stimuli.

The stimuli generator selects the concrete stimuli by distance minimization between the valence/arousal values specified by the control signals and the emotional annotations of stimuli in the databases. Stimuli are selected semantically by pattern matching of the keywords from the stimuli databases against the keywords specified by the control signals. When semantics and emotional properties are specified together, the stimuli generator first finds the stimuli of the requested semantics and then chooses the most appropriate one using emotional distance minimization.

We found tags to be information-poor knowledge-representation mechanisms for stimuli generation (i.e., the keywords in IAPS and IADS are semantically scattered, taxonomically disordered, and subsequently cumbersome for information extraction), and we plan to introduce ontology-based tagging in the existing emotionally and semantically annotated databases in order to achieve more human-readable, intuitive, and information-rich descriptions of stimuli, leading to better extraction of context knowledge.\(^{25}\) A common ontology could thus be used for description of stimuli content in IAPS, IADS, or any other ad hoc emotionally and semantically annotated stimuli database regardless of the media form. This work builds on the current stimuli generator that generates IAPS and IADS stimuli.\(^{26}\) Media forms supported by the stimuli generator are also being extended to video and virtual stimuli in the context of VR exposure therapy and SIT.\(^{27}\) Such a versatile stimuli generator could be a useful therapist’s tool even as a
standalone system for delivering manually controlled multimedia stimuli to the participant during psychotherapy.

**Emotional State Estimator**

Emotional state estimator provides crucial information for adaptation of VR stimulations to the emotional response by estimating the participant’s emotional state repetitively as physiological signals are acquired. The participant’s emotional state is changed in response to the presented stimuli and is generally affected by other influences, both internal and external.

Each valence/arousal output of the emotional state estimator is computed from physiological samples acquired during an interval extending a number of seconds backwards from present moment. Physiological samples collected during this interval are used in computing the various features required for valence/arousal estimation, such as mean, standard deviation, minimum, maximum, and slope. On the basis of feature fusion, the emotional state estimator can continually give concise insight into physiological components of the participant’s emotional state, which is a demanding task for humans. As such, the estimator may also be useful in a standalone fashion, not only in SIT and PTSD exposure therapy but in a broader range of human–computer interaction applications following Picard’s¹¹¹ffective computing paradigm. As briefly reviewed in Lukolja et al.,¹²¹he emotional state estimator can be based on a variety of methods. Our initial experiments related to real-time emotional state estimation from skin conductance and heart rate during emotion elicitation with IAPS pictures and IADS sounds have applied the artificial neural networks.¹²¹The relatively low accuracy of results obtained by participant-independent emotional state estimation has emphasized the importance of customizing the estimator to every individual. Estimation accuracy may also benefit from increasing the number of signals and computed features as well as from fusions of outputs of multiple specialized estimators running simultaneously. Unknown properties of the estimation accuracy as a function of these numerous free parameters call for heuristic global optimization methods, like genetic algorithms, to find the parameter values giving approximately the best accuracy. More comprehensive and challenging extensions would also include assessment of reductions in cognitive abilities during intense emotional states, similar in a sense to VR cognitive performance assessment testing.²⁹

**Adaptive Control Strategy**

The adaptive controller is the central subsystem for optimally individualized VR exposure treatment and SIT, which selects and adjusts all relevant parameters of the system according to the participant’s physiology.⁷ This subsystem relies on the stimuli generator for actual stimuli delivery to the participant and the emotional state estimator for information regarding the his or her emotional state. The adaptive controller can conceivably implement any of the virtually unlimited number of existent control logics, but only a minority may have some practical utility, like strategies that may be compatible with exposure therapy and SIT.

Strategy executed by the adaptive controller may either make use of extensive knowledge supplied by the problem domain experts or not, depending on the problem domain. In the former case, the adaptive controller may best be implemented as the expert system. In this approach, the expert’s knowledge is coded in domain-dependent data structures that represent the rules of the expert’s reasoning, while a separate, domain-independent inference engine executes these rules. The latter case may apply conventional programming, where the strategy is implemented in domain-dependent data structures and execution logic. In either case, temporal information must be appropriately incorporated in the strategy of the adaptive controller, as the participant’s physiology fluctuates with time depending on onsets and durations of stimuli, among various other factors. Additional support for various assessments of reductions in cognitive abilities makes the design of the adaptive controller more challenging. Furthermore, every such cognitive test may also possess a specific appearance and specific outcome measures, potentially adding complexity to the design of the stimuli generator and emotional state estimator.

A few rules⁸ that partially reflect experts’ reasoning in PTSD exposure therapy are outlined as an example:

- If the participant is emotionally detached, then try to engage him or her in the recollection of the traumatic experience via conversation by asking specific questions.³⁰
- If the participant has habituated to the recounting of the trauma (arousal is low), then increase intensity of exposure (e.g., move him or her to the next scenario in the hierarchy).
- If the participant has not habituated (arousal is significant), then keep intensity of exposure (e.g., repeat the same scenario until he or she has habituated)
- If the participant is overwhelmed by the trauma (arousal is too high), then decrease intensity of exposure. The therapist may accomplish this by reinforcing the participant’s feeling of safety.³⁰ In VR exposure therapy, the therapist might also need to take corrective actions to the virtual environment if its therapeutic value is inadequate for the participant’s current situation.

The rules make use of the higher-level representation of emotional state rather than valence/arousal values provided by the emotional state estimator. Mapping the valence/arousal values to these higher-level concepts by the adaptive controller may be naturally conducted with fuzzy logic,⁸ which provides mathematical representation of terms such as low arousal, moderate arousal, and high arousal.

**Stimuli Delivery Algorithm for SIT**

The high-level stimuli delivery algorithm for SIT is sketched in Figure 2. As explained in the introduction, the algorithm is not concerned with acquisition of specific task skills but with experiencing the stressors in order to increase the participant’s resistance to the stress-related psychological disorders.

At the beginning of any session other than the first one, the information from the participant’s earlier sessions is retrieved. This also includes initializing the state of the adaptive controller from the state stored at the end of the previous session. The session proceeds only if the session-should-continue predicate evaluates to true. This predicate may be used to prevent an unbounded number of sessions for a given
session begin
if not first-session
retrieve information from earlier sessions;
end if
if session-should-continue
conduct baseline physiological measurements;
repeat
// Perform exploratory stage.
repeat
select a new stimulus;
expose subject to the stimulus;
rank the stimulus based on the subject’s physiological reactivity;
until start-training
// Perform training stage.
repeat
train habituation to the high-reactivity stimuli;
until stop-training
until end-session
store internal state of the Adaptive Controller;
end if
session end

FIG. 2. High-level stimuli delivery algorithm for stress inoculation training.

participant. After the session proceeds, it includes several minutes of baseline physiological measurements (e.g., without delivering specific stimuli). This is necessary because different sessions may take place on different days and the participant’s physiology may vary between days.

After baseline physiological measurements, the session consists of multiple cycles of exploratory and training stages. In the exploratory stage, the participant is presented with various stimuli from the stimuli database, according to a currently unspecified search algorithm in the stimuli space. Durations of the stimuli may generally be time-limited and/or depend on behavior of the acquired physiological signals. Estimated emotional state from physiology, regardless of its actual representation in this application, may be used for ranking the stimuli based on their impact on the participant’s physiology. Following the exposure to every new stimulus, ranking of stimuli is performed, and a predicate that guards the initiation of the training stage is checked. A possible start-training predicate, open to further refinements, may specify that the number of stimuli that elicit significant physiological reactions must exceed a predefined threshold number.

When the start-training predicate is satisfied, the training stage starts. Here, the participant tries to lower physiological reactivity to the stimuli that have been found to elicit high reactivity in the exploratory stage. Repeated exposures to these stimuli may take place in this stage. The training stage ends when the stop-training predicate is satisfied, which may be defined in various ways. The predicate may include a measure of success of the training stage (e.g., by specifying the minimum required percentage of achieved habituations over the stimuli used in training). In order to avoid an infinite loop in this stage if the participant is unable to achieve the required percentage of habituations, the predicate may also include restrictions on the maximum number of repeated exposures allowed per stimulus. In this case, the assessment of the participant’s progress in training is updated to include inability of the participant to achieve habituation on the particular stimuli. Stimuli to which habituation has not been achieved may be trained in subsequent training stages, together with the newly found high-reactivity stimuli. Exact definition of habituation to a stimulus is left unspecified at this point. However, it is expected to be defined in terms of change in the physiological reactivity relative to the first exposure to the stimulus, taking into account baseline differences if the stimulus is used across sessions.

After a training stage has been completed, the predicate for ending the session is tested. This predicate may consist of various checks, including whether all stimuli from the stimuli database have been encountered during exploratory stages, whether maximum allowed time per session or maximum allowed number of stimuli per session has been exceeded, whether maximum allowed number of exploratory-training cycles have been performed, and so on. If the session should continue, a new cycle with exploratory and training stages is performed. Otherwise, the internal state of the adaptive controller is serialized into the SAKD just before the session ends, to be retrieved when the subsequent session starts.

Conclusion

This work described the concept and implementation of the physiology-driven adaptive VR stimulation, with its potential applications in VR exposure therapy and SIT for high-stress occupations, like military peacekeeping operations. The major subsystems of physiology-driven adaptive VR stimulation and their inner workings were presented. The stimuli generator offers considerable potential for flexible and intuitive presentation of multimedia stimuli to the participant based on specification of their semantics, emotional properties, and media forms. The emotional state estimator performs periodic assessment of the participant’s emotional state from multiple physiological signals, represented concisely according to the valence/arousal dimensional model of emotions. The adaptive controller implements an application-specific closed-loop control strategy that personalizes the stimuli delivery to the participant based on his or her emotional state. The stimuli delivery algorithm for SIT (Fig. 2) supports the participant’s practice of stress-coping skills during presentation of various stressors, which may improve stress resistance and provide potentially protective effects against stress-related psychological disorders.

Evaluation of the physiology-driven adaptive VR stimulation against contemporary methods of prevention and treatment according to various criteria is very important for its practical utility. The most significant and costly evaluation is related to the prevention/treatment efficacy of the physiology-driven adaptive VR stimulation and comparison with the existing methods in a randomized controlled trial.

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References


Address correspondence to: Sinisa Popović
University of Zagreb
Faculty of Electrical Engineering and Computing
Laboratory for Interactive Computer Simulation Systems
Unska 3, 10000 Zagreb, Croatia

E-mail: sinisa.popovic@esa.fer.hr