Wearable Sensors Can Assist in PTSD Diagnosis

Andrea K Webb, Ashley L. Vincent, Alvin Jin
The Charles Stark Draper Laboratory
Cambridge, MA, USA
awebb@draper.com

Mark H. Pollack
Department of Psychiatry
Rush University Medical Center
Chicago, IL, USA

***Abstract*—Post-traumatic stress disorder (PTSD) currently is diagnosed via subjective reports of experiences related to the traumatic event. More objective measures are needed to assist clinicians in diagnosis. Physiological activity was recorded from 58 participants. Participants in the No Trauma/No PTSD group had no trauma exposure and no PTSD diagnosis. Trauma Exposed/No PTSD participants had experienced a traumatic event but did not have PTSD. PTSD participants had experienced a traumatic event and had PTSD. Baseline and emotionally evocative stimulus-related sensor data were collected. Features were extracted from each sensor stream and submitted to statistical analysis. Significant group differences were present during the viewing of two virtual reality videos. Features were submitted to discriminant function analysis to assess classification accuracy. Classification accuracy was between 89 and 92%. The results from this study suggest the utility of objective physiological measures obtained from wearable sensors in assisting with PTSD diagnosis.**

Keywords—PTSD, physiological sensors, feature extraction, classification accuracy

I. INTRODUCTION

Post-traumatic stress disorder (PTSD) can develop following an extreme traumatic stress that involves actual or threatened death or harm to oneself or someone else. It is characterized by reexperiencing of the traumatic event, numbing and avoidance, and hyperarousal [1]. PTSD may be associated with a variety of other disorders, including depression, anxiety, and substance abuse, which can make it difficult to diagnose and treat. PTSD affects both civilians and veterans. The research on United States veterans returning from Iraq reports prevalence rates varying from 4% to 17% [2]. This discrepancy may be due to the self reported nature of diagnosis, with some individuals over reporting to obtain medical benefits and others under reporting due to the stigma of having a mental disorder [3]. Some have estimated the cost of treating returning veterans from Operations Iraqi Freedom and Enduring Freedom with PTSD and depression to be approximately $923 million over the first 2 years [4]. The treatment cost in addition to the loss of productivity and life due to suicide make it essential that PTSD is accurately diagnosed and effectively treated.

One of the primary challenges in accurately diagnosing PTSD is that diagnoses currently are made based upon the patient's subjective reports of their experiences related to the traumatic event. More objective measures are needed to assist in diagnosis. The physiological consequences of PTSD may provide such objective information. Baseline physiological differences are often observed, with Vietnam veterans who have PTSD demonstrating a greater resting heart rate than those without PTSD [5-8]. Resting skin conductance differences also are informative; individuals with PTSD exhibit greater baseline levels than those without [9-10]. These baseline differences, particularly heart rate, are robust, as evidenced in a recent meta-analysis [11].

Individuals with PTSD generally demonstrate increased physiological reactivity as compared to those without PTSD. Acoustic startle is a commonly used method of eliciting physiological responding. Those with PTSD tend to show greater heart rate reactivity in response to loud tones as compared to those without PTSD [12-13]. Findings for electrodermal activity in response to startle stimuli have not been as consistent as the findings found for heart rate. Some studies have shown a slower slope in recovery following startle cues in individuals with PTSD [14]. Others have found no difference in the individual slopes of the startle responses, but have shown a decreased level of habituation, with the last startle in a series producing a significantly greater skin conductance response in individuals with PTSD [15]. One study that did not find an exaggerated startle response did find a difference in the degree of habituation to startle stimuli among people with and without PTSD [16].

In addition to general startle and arousal activity, individuals with PTSD may show differential reactivity in response to specific cues. Using standardized combat sound cues such as helicopters, gun, and mortar fire, individuals can be classified as having PTSD or not based upon the maximum level of heart rate reactivity [17-18]. Other studies have used idiographic cues that are specific to an individual's traumatic experience. Script-driven imagery techniques have elicited greater heart rate and skin conductance responses in those with PTSD as compared to those without [19]. In another study, nurses with PTSD who served during Vietnam demonstrated greater heart rate and skin conductance responses when asked to imagine specific experiences. This difference was not found in response to standardized cues [5]. In both of these cases, physiological differences were present in the absence of differences in self-reported stress levels. Cues other than mental imagery also demonstrate specificity, as evidenced by greater skin conductance responses in individuals with PTSD when given words related to the past

This work was funded by The Charles Stark Draper Laboratory.

978-1-4799-0330-6/13/$31.00 ©2013 IEEE

traumatic event [20]. Watching videos of combat-related stress resulted in increased heart rate in Vietnam veterans with PTSD as compared to those without, as compared to non combat-related videos [21]. Taken together, these studies have shown that both standardized and idiographic trauma cues may be useful in the diagnosis of PTSD.

Virtual reality is a relatively new technology that could be used for the presentation of both standardized and idiographic trauma cues. Many experts believe that virtual reality may be used in the prevention, assessment, and eventual treatment of PTSD [22]. The multimodal aspect of virtual reality provides an immersive environment [23] that may be more useful than the use of traditional cues alone. Several recent studies have found that virtual reality exposure reduced PTSD scores [24-25]. Virtual reality has even been used on soldiers while serving in an active theater to enhance already existing exposure therapy treatments [26].

Taken together, it is apparent that objective physiological measures can be used to discriminate among those with and without PTSD and that promising new technologies are available for the presentation of stimuli to evoke physiological responses. The goal of the present work was to ascertain the utility of objective physiological measures elicited in response to emotionally evocative stimuli in discriminating among those with and without trauma exposure and PTSD.

II. Method

A. *Participants*

Participants were recruited using print and electronic advertisements (i.e., Craigslist, Recruitmilitary.com), and flyers and pamphlets dispersed in the areas of Boston, MA and Tampa, FL. Of the 58 male participants who completed the protocol, 19 were in the No Trauma/No PTSD Diagnosis group, 23 were in the Trauma Exposed/No PTSD Diagnosis group, and 16 were in the PTSD Diagnosis group. Demographic information is presented in Table 1.

TABLE I. Demographic information

Variable	**No Trauma/No PTSD**	**Trauma Exposed/No PTSD**	**PTSD**
Age	*M* = 30.2 (*SD* = 7.92)	*M* = 26.9 (*SD* = 3.61)	*M* = 28.8 (*SD* = 4.29)
Years of Education	*M* = 15.5 (*SD* = 2.04)	*M* = 14.3 (*SD* = 1.33)	*M* = 14.1 (*SD* = 1.67)
Employment			
Unemployed	3	6	9
Full-time	6	9	3
Part-time	6	5	2
Other	4	3	2
Ethnicity			
Caucasian	15	18	14
Asian	1	1	0
African-American	2	1	1
Hispanic	1	3	1

A. *Apparatus*

BIOPAC. The BIOPAC system was used to collect respiration, skin conductance (SC), electrocardiograph (ECG), and finger pulse amplitude (FPA) measures. Respiration was recorded from a transducer secured around the upper chest with a Velcro strap. SC was recorded from disposable Ag-AgCl electrodes placed on the distal phalanges of the index and middle fingers of the nondominant hand. ECG was recorded from modified Lead II (lower left and upper right chest). FPA was recorded from the tip of the ring finger on the nondominant hand. Data were collected at 500Hz.

eMagin Z800 3D Visor. This head-mounted system provides a high-contrast virtual image. The visor includes a head tracking capability that allowed the participant to have a 360 degree view during stimulus presentation. Participants wore head phones when using the 3D visor.

B. *Procedure*

Telephone Quick Screen. All participants completed a Telephone Quick Screen (TQS) prior to being scheduled for an appointment. The TQS allowed research staff to obtain general demographic, medical, and substance use information to detect obvious disqualifying conditions. In addition, participants with obvious trauma confounds were excluded; this included those individuals who self reported personally relevant traumas as opposed to military related traumas. After completing the TQS, those who appeared eligible were scheduled for a research session.

Research Session. Data collection occurred during a single session. Participants were told that they would earn $25 per hour for their time in the study and could expect it to last approximately three hours for a total of $75 payable upon study completion.

After signing the informed consent form, participants completed a demographic information questionnaire, and both the State Trait Anxiety Inventory (STAI; Spielberger et al., 1983) and the Positive and Negative Affect Schedule (PANAS; Watson et al., 1988) to determine baseline measures of anxiety and affect. All participants also completed the Traumatic Events Questionnaire (TEQ, Revised 7-2004; Vrana & Lauterbach, 1994) and the Structured Clinical Interview for DSM-IV-TR Axis I Disorders (SCID-I/P, 11/2002), Posttraumatic Stress section (F. 29). These assessments provided an inventory of the participants' traumatic experiences and related symptoms. Additionally, they assisted in confirming which study group the participant fell into: PTSD Diagnosis, Trauma Exposed/No PTSD Diagnosis, or No Trauma/No PTSD Diagnosis. Those who appeared to be in either of the first two groups also completed the Clinician-Administered PTSD Scale (CAPS; Blake et al., 1995) for confirmation of and more detail regarding symptoms.

Next, researchers assisted participants in attaching the BIOPAC system to monitor physiological activity during stimulus presentation. Once outfitted with the BIOPAC, data collection began with a 10 minute baseline period; participants

were asked to relax, sit quietly, and stay awake. At the end of the baseline period participants were presented with a series of 8 audio startle stimuli presented through a speaker placed in the room. Noise bursts were less than 120 dBA and were separated by time intervals varying between 5 and 20 seconds.

Next, the participants completed three stimulus presentation trials; trial order was counterbalanced and randomized across participants. During the trials, participants listened to 24 sounds from the International Affective Digitized Sound system (IADS; Bradley & Lang, 1999), viewed 24 images from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2008), and viewed two 5-minute 3D videos using images and sounds from the Virtual Iraq software. One video was designed to emulate a foot patrol in a city setting, and the other was a humvee driving scenario. Each video contained five events that appeared approximately every 45 seconds. Events were designed to increase in intensity over the duration of the video (e.g., event 1 was a helicopter flying overhead, event 5 was an insurgent firing a weapon). Participants were exposed to sample IADS and IAPS prior to beginning the full trials, allowing them the opportunity to withdraw if uncomfortable with the sample content.

Upon completion of all stimulus presentation trials, participants were asked to again complete the STAI (Y1) and PANAS (present) as well as a stimulus reaction questionnaire allowing participants to provide qualitative responses to questions about the stimuli they had just experienced. Participants were then provided with the opportunity to ask questions or provide feedback regarding the study. Finally, participants were paid for their time, thanked, and escorted out of the building.

B. Data Analysis Approach

The analyses presented here focus on skin conductance and interbeat interval for the baseline and VR portions of the protocol. CPSLAB (Scientific Assessment Technologies, Salt Lake City, UT) was used to edit and analyze the data. Artifacts were removed from the data via interpolation.

Response Curves. Response curves were computed for each signal. For the skin conductance data, the response curve was defined by the sequence of values. For the ECG data, R-peaks were identified and used to create an interbeat interval (IBI) waveform. For the baseline period, a response curve was computed for the last three minutes of the 10 minute baseline period. For the VR videos, a response curve was computed for each of the five video events. The response curve began at the onset of the event and ended 20 seconds later.

Feature Extraction. Several features were extracted from the response curves:

Area to Full Recovery was the area under the response curve from response onset to the point of full recovery.

Area to Half Recovery was the area under the response curve from response onset to the point of half recovery.

Peak Amplitude was computed by identifying high and low points on the response curve and computing the difference between each low point and every succeeding high point. Peak amplitude was the greatest difference.

Standard Deviation was the standard deviation of samples that defined the response curve.

Rise Time from the First Low Point was the time from the first low point in the curve to the time of peak amplitude.

Rise Time from Response Onset was the time from the onset of the physiological response to the time of peak amplitude.

Rise Rate from Response Onset was the amplitude divided by the rise time, computed from the onset of the physiological response.

Rise Rate from First Low Point was the amplitude divided by the rise time, computed from the first low point in the response curve.

Level was the average of the data points within the response window.

Within-Subject Standardization. For each feature, a measurement was obtained for each VR video event. The 10 measurements were converted to z-scores for each subject.

III. Results

A. Baseline IBI

Due to the multi-site design, analyses of site differences were conducted. A 2 (Site: Massachusetts, Florida) x 3 (Group: No Trauma/No PTSD Diagnosis, Trauma Exposed/No PTSD Diagnosis, PTSD Diagnosis) analysis of variance (ANOVA) for IBI revealed a significant main effect of Site for mean and standard deviation ($F(1,49) = 5.74$, $p = .02$, $\eta_p^2 = .11$ and $F(1,49) = 5.61$, $p = .02$, $\eta_p^2 = .10$, respectively) with the participants in Florida demonstrating longer ($M = 966.91$, $SE = 30.70$) and more variable ($M = 77.97$, $SE = 6.36$) IBI as compared to Massachusetts participants ($M_M = 873.39$, $SE_M = 24.12$; $M_{SD} = 58.82$, $SE_{SD} = 5.00$). The Site X Group interaction was not significant; however, the simple effect of Site within the No Trauma/No PTSD Diagnosis group was significant for both mean and standard deviation ($F(1,49) = 4.34$, $p=.04$, $\eta_p^2=.08$ and $F(1,49) = 5.99$, $p = .02$, $\eta_p^2 = .11$, respectively), indicating that within the No Trauma/No PTSD Diagnosis group, the Florida participants had longer ($M = 996.22$, $SE = 48.54$) and more variable ($M = 83.91$, $SE = 10.06$) IBI as compared to the Massachusetts participants ($M_M = 857.30$, $SE_M = 45.76$; $M_{SD} = 50.09$, $SE_{SD} = 9.48$). The IBI mean data are presented graphically in Fig. 1. Because these site differences were present, Baseline IBI mean and standard deviation were used as covariates for subsequent analyses.

Analysis of Baseline IBI results showed no significant group differences for mean or standard deviation ($F(2,49) = .61$, $p = .56$ and $F(2,49) = 1.26$, $p = .29$, respectively), although the trend was for those in the PTSD Diagnosis group to have shorter IBI (higher heart rate) and less variable IBI as compared to the other two groups. There was a marginally significant negative relationship between mean IBI and lifetime severity of PTSD ($r = -.46$, $p = .05$), indicating that more severe PTSD symptoms were associated with shorter IBI (higher heart rate). These data are presented graphically in Fig. 2.

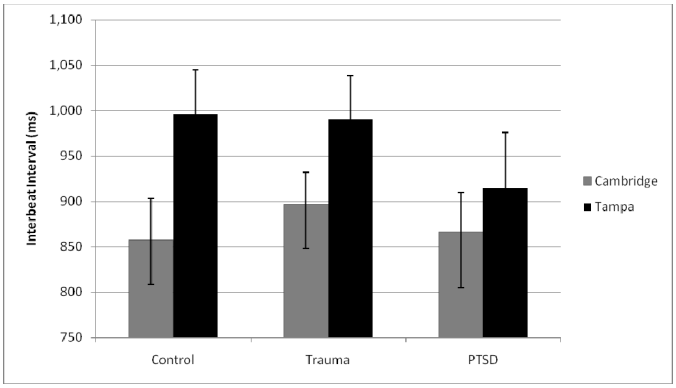

Fig 1. Mean IBI for Cambridge and Tampa groups.

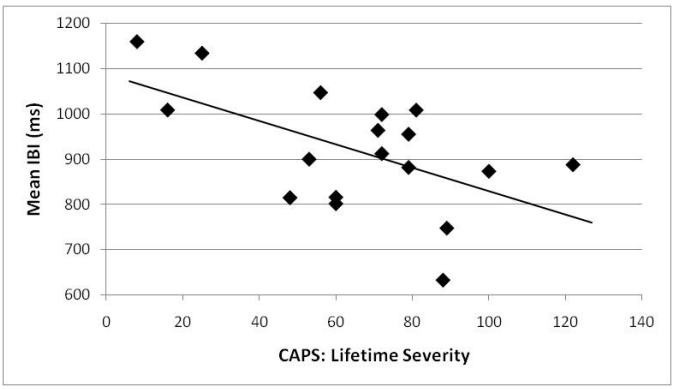

Fig 2. Relationship between mean IBI and Lifetime PTSD Severity.

B. VR Videos

Difference scores were calculated by subtracting SC amplitude scores for each event in video 1 from scores for each event in video 2, such that negative difference scores indicate a decrease in SC amplitude from video 1 to video 2.

A 3 (Group: No Trauma/No PTSD Diagnosis, Trauma Exposed/No PTSD Diagnosis, PTSD Diagnosis) x 5 (Video event) repeated measures ANOVA was conducted to examine changes in SC difference scores across the five video events. A significant main effect of Group was found ($F(2,53) = 4.38$, $p = .02$, $\eta_p^2 = .14$). Bonferroni corrected pairwise comparisons revealed significantly greater decreases in SC amplitude in the No Trauma/No PTSD Diagnosis group ($M = -12.37$, $SE = 2.33$) as compared to the PTSD Diagnosis group ($M = -2.31$, $SE = 2.48$), $p = .01$. Significant simple effects of group were found within Event 1 (Aircraft) and Event 3 (IED; $F(2,53) = 4.96$, $p = .01$, $\eta_p^2 = .16$ and $F(2,53) = 4.92$, $p = .01$, $\eta_p^2 = .16$, respectively) and Bonferroni corrected pairwise comparisons revealed the same trend of significantly greater decreases in the No Trauma/No PTSD Diagnosis group as compared to the PTSD Diagnosis group for both events (Event 1: $M_{\text{No Trauma/No PTSD}} = -14.05$, $SE_{\text{No Trauma/No PTSD}} = 3.34$ and $M_{\text{PTSD}} = .864$, $SE_{\text{PTSD}} = 3.54$; Event 3: $M_{\text{No Trauma/No PTSD}} = -16.39$, $SE_{\text{No Trauma/No PTSD}} = 3.20$ and $M_{\text{PTSD}} = -1.77$, $SE_{\text{PTSD}} = 3.39$), ps = .01. These data are presented in Fig. 3.

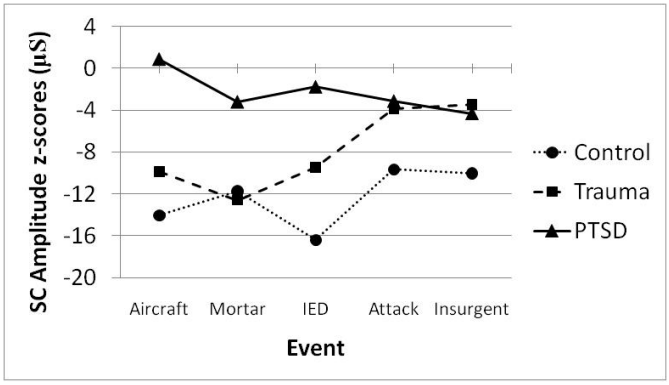

Fig 3. Skin conductance amplitude change across first and second VR videos.

Based on the within-video habituation seen in the No Trauma/No PTSD Diagnosis and Trauma Exposed/No PTSD Diagnosis groups, it was hypothesized that the decrease in SC amplitude in Video 1 would increase the average difference score for these two groups, thereby masking group differences that may actually exist. A second repeated measures ANOVA was conducted to examine changes in difference scores across the first three events only. Results revealed a significant main effect of Group ($F(2,53) = 5.85$, $p = .01$, $\eta_p^2 = .18$) and Bonferroni corrected pairwise comparisons showed significantly greater decreases in SC amplitude in the No Trauma/No PTSD Diagnosis ($M = -14.06$, $SE = 2.62$) and Trauma Exposed/No PTSD Diagnosis ($M = -10.65$, $SE = 2.37$) groups when compared to the PTSD Diagnosis ($M = -1.37$, $SE = 2.78$) group ($p = .01$ and $p = .04$, respectively). These results suggest a greater level of habituation across videos in the No Trauma/No PTSD Diagnosis and Trauma Exposed/No PTSD Diagnosis groups as compared to the PTSD Diagnosis group when focusing on only the first three video events.

C. Classification Accuracy

The IBI and SC features described in the Method section were computed for each of the ten VR video events (five from each of the two videos). These features were submitted to stepwise discriminant function analysis (DFA) to assess classification accuracy. Three DFAs were performed to assess which variables were selected for No Trauma/No PTSD vs. Trauma Exposed/No PTSD, No Trauma/No PTSD vs. PTSD, and Trauma Exposed/No PTSD vs. PTSD pairings of the group variable. Notably, DFA selected different variables for each of these analyses: four IBI features (two from the first video and two from the second) and 1 SC feature from the second video were selected for No Trauma/No PTSD vs. Trauma Exposed/No PTSD; three IBI features (one from the first video and two from the second) and three SC features (two from the first video and one from the second) were selected for No Trauma/No PTSD vs. PTSD; and three IBI features (one from the first video and two from the second) and two SC features from the first video were selected for Trauma Exposed/No PTSD vs. PTSD. Results are presented in Tables 2-4. Percent correct for each group is highlighted in bold.

TABLE 2. CLASSIFICATION ACCURACY FOR NO TRAUMA/NO PTSD AND TRAUMA EXPOSED/NO PTSD

		Predicted		
		No Trauma/No PTSD	Trauma Exposed/No PTSD	
Actual	No Trauma/No PTSD	**16 (94.1%)**	1 (5.9%)	
	Trauma Exposed/No PTSD	2 (9.1%)	**20 (90.0%)**	
Total				92.3%

TABLE 3. CLASSIFICATION ACCURACY FOR NO TRAUMA/NO PTSD AND PTSD

		Predicted		
		No Trauma/No PTSD	PTSD	
Actual	No Trauma/No PTSD	**16 (94.1%)**	1 (5.9%)	
	PTSD	2 (15.4%)	**11 (84.6%)**	
Total				90.0%

TABLE 4. CLASSIFICATION ACCURACY FOR TRAUMA EXPOSED/NO PTSD AND PTSD

		Predicted		
		Trauma Exposed/No PTSD	PTSD	
Actual	Trauma Exposed/No PTSD	**19 (86.4%)**	3 (13.6%)	
	PTSD	1 (7.7%)	**12 (92.3%)**	
Total				88.6%

IV. DISCUSSION

The present study demonstrated that objective physiological measures obtained in response to non-idiographic emotionally evocative virtual reality stimuli can discriminate among individuals with and without trauma and with and without PTSD at levels well above chance. Consistent with prior work [5,17,19], it was found that cardiac and electrodermal activity discriminate well among those with and without PTSD. Notably, optimal features selected from the virtual reality videos differed for each of the pairwise classification analyses. This suggests that several different diagnostic algorithms may be needed for optimal performance in point of care and field settings. Although the classification results are quite promising, false positives and false negatives still were present. Additional analyses will be performed to understand the characteristics of the participants who were misclassified (e.g., did they report less anxiety, did they show little physiological reactivity, etc.). This information will be used to tailor future classification algorithms to develop a more individualized approach.

In contrast to some prior work [5-8], significant baseline group differences in cardiac activity were not present in the current work. However, the trend was for those with PTSD to have shorter IBI (higher heart rate) than those in the other two groups. Additionally, those with more severe PTSD tended to have higher baseline heart rate than those with less severe PTSD. There was a significant difference in baseline IBI between the two data collection sites. It is not clear what led to this difference, but it will be important in future multi-site studies to look for and statistically correct for such differences if they are present.

The virtual reality videos were effective in eliciting physiological responses in all three of the groups. Those in the PTSD Diagnosis group tended to have skin conductance responses that did not habituate across the presentation of the two virtual reality videos, whereas the No Trauma/No PTSD and Trauma Exposed/No PTSD groups did tend to show habituation, particularly when looking at only the first three of the five video events. This lack of habituation in the PTSD group supports what others have found and what is known about the physiological consequences of PTSD.

A. *Limitations and Future Directions*

Participants in the current study were male veterans. Future work should be done with female veterans and civilians to ascertain the effectiveness of this approach in those populations. Additionally, the sample size in the present study was small. The results should be replicated in a larger sample. Participants in the current study were generally free of comorbid mental health conditions. As noted previously, PTSD is often comorbid with a variety of other disorders. Future work should be done with a more heterogeneous sample to ascertain the generalizability of this approach and the findings.

The system used to collect physiological responses is a currently available off-the-shelf product. The system and sensors are relatively easy to use with some technical experience. One of the long-term goals of this line of research is to develop a portable and easy-to-use system that can be used at point of care and in the field to assist with diagnosis and treatment monitoring. With some effort, the currently available technology can and should be modified to simplify the application of sensors and make it more portable for use in a variety of settings. Future work also should examine the effects of different virtual reality scenarios and levels of visual fidelity in eliciting physiological responses among those with and without PTSD.

B. *Conclusions*

The current work has shown that wearable sensor technology can be used to accurately classify those with and without PTSD at rates well above chance. While promising, additional work is needed to replicate and assess the generalizability of the findings. Additionally, more work is needed to refine the algorithms and modify the technology to facilitate ease of use in a variety of settings. This work holds significant promise for the development of a tool to assist in diagnosis and treatment monitoring to ultimately improve the outcomes of those with mental health disorders.

ACKNOWLEDGMENT

The authors thank Albert ‘Skip’ Rizzo at the Institute for Creative Technologies for providing the Virtual Iraq software used for the creation of the virtual reality videos.

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