Development of a Data Management Tool for Investigating Multivariate Space and Free Will Experiences in Virtual Reality

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Abstract

Virtual Reality (VR) has become mature enough to be successfully used in clinical applications such as exposure therapy, pain distraction and neuropsychological assessment. However, we now need to go beyond the outcome data from this research and conduct the detailed scientific investigations required to better understand what factors influence *why* VR works (or doesn't) in these types of clinical applications. This knowledge is required to guide the development of VR applications in the key areas of education, training and rehabilitation and to further evolve existing VR approaches. One of the primary assets obtained with the use of VR is the ability to simulate the complexity of real world environments, within which human performance can be tested and trained. But this asset comes with a price in terms of the capture, quantification and analysis of large, multivariate and concurrent data sources that reflect the naturalistic behavioral interaction that is afforded in a virtual world. As well, while achieving realism has been a main goal in making convincing VR environments, just what constitutes realism and how much is needed is still an open question situated firmly in the research domain. Just as in real "reality", such factors in virtual reality are complex and multivariate, and the understanding of this complexity presents exceptional challenges to the VR researcher. For certain research questions, good behavioral science often requires consistent delivery of stimuli within tightly controlled lab-based experimental conditions. However, for other important research questions we do not want to constrain naturalistic behavior and limit VR's ability to replicate real world conditions, simply because it is easier to study human performance with traditional lab-based methodologies. By doing so we may compromise the very qualities that comprise VR's unique capacity to mimic the experiences and challenges that exist in everyday life. What is really needed to address scientific questions that require natural exploration of a simulated environment are more usable and robust tools to instrument, organize, and visualize the complex data generated by measurements of participant behaviors within a virtual world. This paper will briefly describe the rationale and methodology of an initial study in an ongoing research program that aims to investigate human performance within a virtual environment where unconstrained "free will" exploratory behavior is essential to research questions that involve the relationships between physiology, emotion and memory. After a discussion of the research protocol and the types of data that were collected, we describe a novel tool that was borne from our need to more efficiently capture, manage and explore the complex data that was generated in this research. An example of a research participant's annotated display from this data management and visualization tool is then presented. It is our view that this tool provides the capacity to better visualize and understand the complex data relationships that may arise in VR research that investigates naturalistic free will behavior and its impact on other human performance variables.

1   The Challenge for Virtual Reality Research

Virtual reality (VR) has been transforming the domain of clinical therapy by providing a plausible simulacrum to real world experiences. Perhaps the application of VR for the treatment of anxiety disorders, especially simple phobias, provides the most consistent reports of positive therapeutic outcomes (see reviews in Glantz, Rizzo & Graap, 2003; Rizzo & Kim, 2005). This approach has allowed for patients to be immersed within virtual environments that provide the graduated therapeutic exposure to relevant stimuli that are the focus of their fear or condition. While it is now clear that these therapeutic effects exist, there is much to be done to understand the scientific basis for such VR efficacy. In order to examine virtual reality beyond the realm of clinical outcomes, new kinds of tools are required that facilitate the scientific study of the stimulus parameters and resulting responses that occur in such simulated worlds.

Virtual reality is hampered from full experimental validity by the very attribute that makes it an excellent device for the replication of real world challenges: it is exceptionally complex and multivariate. A typical VR

session generates immense amounts of data, even for a relatively short experience (8-10 minutes), and VR worlds that allow for each subject to make their own choices within the environment further complicate this data collection and analysis. This type of "free-will" experience can be subverted by constraining the subject's path or choices within the environment (Morie 2002), but some research questions are better served by permitting such *agency*, especially those in which observing the participant's uncoerced choices are the focus of study. However, in-depth investigation of agency in VR is not a simple task and as yet no specialized tools exist to instrument, organize, and visualize the ensuing complex data produced in such free will scenarios. This paper will present a research protocol that allows such agency in a VR application to investigate naturalistic free will behavior and its impact on other human performance variables (i.e., physiology, emotion and memory). This will involve a discussion of the research question, the types of data that was collected, and will describe a novel tool that was borne from our need to more efficiently capture, manage and explore the complex data that was generated in this research. An example of an annotated display from a research participant will also be presented. We believe this tool will provide the capacity to better visualize and understand the complex data relationships that may arise generally in VR research and lead to a more thorough understanding of the unique assets and limitations that VR offers human behavioral research.

2   The Sensory Environments Evaluation Research Program

At the Institute for Creative Technologies (ICT), the Sensory Environment Evaluation (SEE) research program is building and investigating a series of virtual environments (VEs) focusing on arousal states and behaviors when humans naturalistically interact within emotionally evocative scenario conditions. Our first experiment evaluates the memory durability afforded by an emotionally rich VE, with the ultimate goal of making more effective virtual worlds for learning. In addition, we are studying the effects of *priming* on both behavior and the emotional valence of the VE experience. This research was inspired in part by recent findings that clearly show interconnectedness among emotions, cognition, learning and behavior. This research also indicates that emotions cannot be easily dismissed when focusing on pedagogical goals (cf. Damasio, 1994; Dolan, 2002; Role, 1999). Emotions can also heighten the attention and response to visual cues (Lane, Chua & Dolan, 1999), and this may be true for other senses as well.

   Ultimately we would like to empirically measure emotional responses of the VE participants under varying conditions that systematically manipulate the challenges that typically occur during natural exploration in the real world. Within this research, we use standard psychophysiological measures of heart rate (EKG) and skin conductance (SCR) to capture arousal states. While these measures cannot tell us what specific emotions are being experienced, they do provide information on participants' reactions that can be correlated in time to the various emotional trigger stimuli that we deliver within the virtual world. We also record detailed behavioral data of each participant's exploratory actions within the virtual world, typically encompassing a five to ten minute session sampled at 20 frames per second per subject. As well, we are investigating the relationship between subject characteristics (i.e., immersive tendencies, computer familiarity, time spent playing computer games, etc.), physiology, naturalistic exploration, and how this influences memory for the events that occur in the virtual world.

   As this research progressed, we quickly realized that the amount of data we were collecting to support our investigation was vast and unwieldy. After the first round of 65 test subjects in our initial study, we found it necessary to temporarily move our focus to creating tools that would allow us to adequately examine the data our study was generating. We call this evolving tool set, *Phloem*, after the channels in botanical life that serve as nutrient (information) support, transport and storage within the plant. Even in its early stages, Phloem has demonstrated value for increasing our understanding of the complex data produced in this study.

3   Experiment Design Process

The SEE Project's investigation of emotionally compelling VEs comprises a threefold experimental approach. First we base the design process on the various sensory inputs available to the VR practitioner (sight, sound, smell, haptics), and attempt to determine how these can be effectively combined to elicit emotional responses. Second, we test research subjects in an emotionally "provocative" VE and measure their physiological arousal states and behaviors. Third, with our findings from these subject evaluations, we expect to devise a methodology that uses emotions to increase the effectiveness of virtual environments for a variety of purposes. Our first study is examining the influence of priming on engagement and performance in a virtual world.

3.1.1   Independent Variable - Priming

For our first experiment we focused on one means to establish an emotional connection between the subject and the VE. We chose the independent variable of *priming*, as described in (Schacter and Buckner, 1998) and (Tulving and

Schacter, 1990), to give participants a context for what they were about to experience. Such priming is sometimes also referred to as the instructional set and helps subjects construct a schema by which their task is understood.

Each participant was randomly assigned to one of two priming groups. In the first group, participants received priming that instructed them about the goal of their impending task in the VE in the context of an entertaining video game that they were about to play. The second group received a briefing that indicated they would experience a serious military training exercise. The priming process actually started when the participants were brought into a room to fill out demographic and self-report questionnaires (described below). Themed posters decorated the walls of the room: game-based for the game primed participants and serious military posters for those undergoing the second form of priming. These were not referred to, but rather formed a backdrop in the room. In fact, if asked about them, the evaluators would say they could not comment about anything in the room. The principal priming mechanism was a two minute video clip delivered by an appropriately themed narrator immediately preceeding the VE experience. The basic instructions, goals and VR environments were exactly the same for each group. Only the manner of presentation and the context differed. We tested 64 subjects, ages 18-40, drawn from a standard university population, divided evenly across these two groups. We were especially interested in determining if the two priming conditions would have a significant affect on participants' behavioral and arousal measures.

3.1.2   Subject Variables

Our experiment used standard pre-experience instruments to collect pertinent subject characteristics. These included a modified Immersive Tendencies Questionnaire, or ITQ (Witmer & Singer, 1998), the Simulator Sickness Questionnaire (SSQ) (Kennedy, Lane, Berbaum & Lilienthal, 1993) and the Virtual Environments Questionnaire (VEQ) (Usoh, Catena, Arman & Slater, 2000). We made some small modifications to the ITQ pertaining to questions about participants' history and experiences with various types of video games. This data allowed for the comparison between game players and non-game players to see if this subject characteristic had any bearing on the outcomes of primed behavior observed in the simulation. Our new questions allowed us to further divide subjects into the specific type of games they played and/or preferred: first person shooter, role playing, puzzle, etc.

3.1.3   Subject Arousal

Subjects were next outfitted with physiological sensors to record EKG and SCR. The participant was then brought into the testing room where the VR viewing and navigation equipment was explained and fitted. To minimize unfamiliarity with the VR devices in use (an *InterSense* acoustic and inertial tracker, with X and Y dimensions mapped onto a joy stick, and Z, pitch, roll and yaw mapped onto a sensor mounted on a *Kaiser Pro-View* head mounted display, or HMD) each participant was given a practice session in a VE "Tutorial Room". This neutral space allowed the subjects to experience and practice the full range of movements and observational skills required for the VR evaluation scenario. We found this to be a necessary step as, absent such familiarization, participants often explored and interacted in the virtual world with a very limited range of movement, such as not crouching or bending down, and looking only straight ahead with "tunnel vision".

3.1.4   Subject Behaviors

Once the participant gained adequate interaction familiarity within the tutorial room (determined by the evaluator and subject together) the participant was requested to return to the starting point of the tutorial room without instructor assistance. This established a baseline metric we refer to as the "free-walking baseline" for the physiological data. It was inspired by the "vanilla baseline" described by Jennings et al., (1992), who suggested giving a simple cognitive task to help standardize the mental activity of all subjects during the baseline period, since not all subjects will follow the instructions for a resting baseline (i.e. to sit quietly, relax, keep eye closed, etc.). A free walking baseline should provide a more natural baseline measure as the subject, being engaged in a simple task, is less affected by the anticipation of a (stressful) task or the experiment itself. This free walking baseline also allows us to compensate for any impact the overhead of using the VR equipment might induce (e.g. anxiety due to different proficiency levels in using a joystick from subject to subject, using the head mounted display, being tethered to cables, etc.). Following this, the core of the experiment began. Depending on the random assignment of conditions, the participant was shown one of the two priming video clips in the HMD that outlined the mission to be undertaken in the VE.

3.1.5   Free agency experience and empirical research
The experiment required each subject to play the role of a forward scout in a military-style scenario, and to determine whether rebels or refugees inhabit an area of suspicion. In this regard, the mission (as described in the priming videos) is basically an observational exercise, but we add a simple objective of dropping a GPS transmitter near a specific building if enough clues indicate that rebels are inhabiting the target area. Because this virtual mission takes place at night we have named it *DarkCon* (see Figure 1).

Figure 1: A participant in the HMD and a scene from the VE experiment world: *DarkCon*

Given their mission briefing instructions, participants knew what they needed to do and where they needed to go in the *DarkCon* environment. They could choose to follow the mission to the best of their ability, or they might not. Because of the free will given to the participants, each experience was, in essence, unique. Not having identical experiences within experimental conditions may appear to be a problem when embarking on studies in VE, but it is this agency that is precisely why we are interested in such experiences. Each person's choices and decisions within the unscripted world are his or her own. Such choice was not only necessary for this particular study, but also had rich implications for individualized training or education that includes cognitive decision-making. An exception to this free agency is that we made it virtually impossible to complete the mission without being discovered. There were several variations on this discovery ending (i.e., vicious dog attacks, landmines, being shot) and all were designed to elicit strong arousal states. We also included a segment of the environment where participants' motions were naturalistically more constrained: a culvert in which subjects start out from that has only one direction of traversal in order to get to an outside environment. As long as participants traverse the full length of the culvert (as did 99% of them) then we have a component of the experience that is roughly the same for each subject. In this way we have three varying conditions within one experiment: a constrained path through the culvert (which still allows for free will in terms of what they look at and how long they linger in any part of the space), an unconstrained outdoor environment, and a "high anxiety-producing" end of scenario.

We realize this is a challenging approach to both data collection and analysis, and consequently needed to apply some structure to our quantification process. For example, we divided the experience into three distinct segments, or epochs, that corresponded to the varying degrees of free will agency described above. The first epoch was defined as the period when the subject was within the constrained culvert space. The second is the time in the exterior environment (very unconstrained) and the third is at the end of scenario segment where all subjects meet a bad ending designed to provoke heightened arousal.

3.1.6 Dependent Variables - Memory

The primary dependent variable in this initial study was memory for the characteristics of the VE. The memory measure assessed pure recall and queried the participant about his or her actions and observations while within the Darkcon VE, including detection of such items as weapons, vehicles and people. One assessment was administered immediately upon completion of the experience (*Immediate Recall*) and the second assessment was conducted by telephone one week later (*Delayed Recall*). We termed the difference in these two scores the *Memory Durability* score. Since agency allowed subjects to explore the Darkcon environment in unique ways, the meaning of these values required an "experience" processing tool that could indicate what objects the subject actually "saw" during free will exploration of the environment.

4 Data Mining in Multivariate Dataspace

Within our first experiment we collected several types of data, both qualitative and quantitative, some of which have been previously described in this paper. Qualitative data included the aforementioned participant reports: questionnaires administered both before and after the VE experience and the two memory assessments. The quantitative data included the full experience biometric recordings of EKG and SCR measures that contained annotations of significant events. Also collected was the participants' behavior in the VE (six degrees of freedom including x, y location, z altitude for stoop/stand, and angular head orientation (pitch, roll and yaw) to determine what was being looked at). We used some of this raw data to derive other metrics, such as heart rate (HR) from the EKG.

4.1 Visualization of behavior and arousal data

The sheer quantity of such participant data motivated development of the Phloem tool set to more effectively manage multiple concurrent streams of data. The first task was to create a visual display of the physiological (arousal) and behavioral data.

4.1.1 Basic data capture and display

Phloem works in conjunction with the data captured by the engine that drives the real-time scenario. This engine includes information about every object and every event in the experience and is capable of producing a log file that contains this information. The log file also contains the numerical values of the x, y, and z position and head orientation of the subject sampled 20 times per second by an InterSense head tracking unit for the duration of the experience (typically 5-10 minutes per subject). Phloem presents the data in an easy-to-scan user interface, making the examination of the recorded data easier. Phloem also uses this data to drive a perfect re-enactment of the experience by feeding it back to control the display parameters of the scene, allowing for a visual playback of each participant's actions. This playback is scrubbable, like a video recording/playback tool, so a researcher can follow participants forwards or backwards, or examine what they do in detail. Phloem automatically reads any key events or interest areas of any experience from the engine data (for example, stimuli such as bats, or a passing truck in DarkCon) and automatically presents these as choices to the researcher via drop down menus. If an event is chosen from this menu, the playback will jump directly to that section. Phloem can also read in and display both sets of physiological signals for each subject, and show them synched to the re-enactment (see Figure 2).
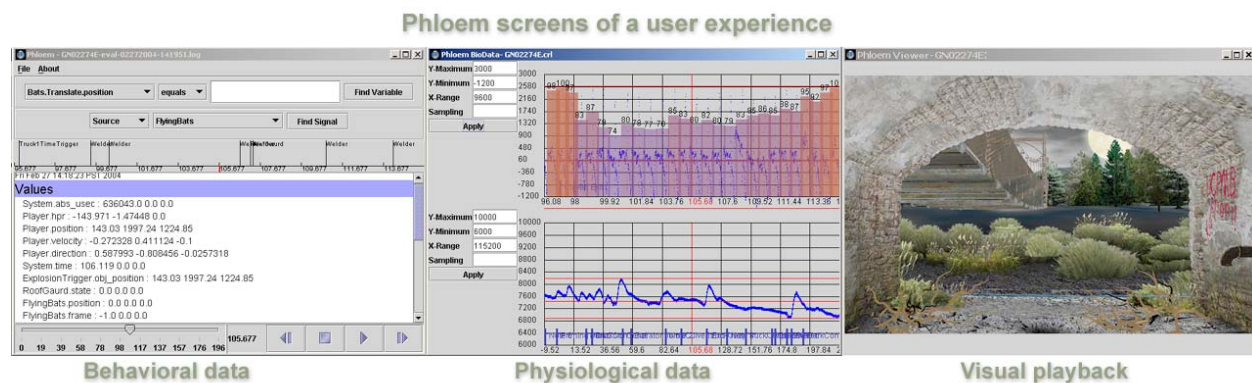

Figure 2: Data as shown by the most recent Phloem visualization tool

4.1.2   More detailed queries

Phloem goes beyond the playback features described above. As it stores all the data from the experience, customized queries can be designed to pull specific information of interest from that data. The behavioral data contains information such as how long a participant took to go through the world as well as where and for how long the subject remained at any particular location in the VE. This allows us to ask such questions as: Did the subject spend a great deal of time in the culvert tunnel, for example, indicating perhaps that the participant was taking greater care in their observations? What was the length and shape of the path they traversed? How much time was spent in the protected culvert compared to the time spent in open space outside the tunnel? With custom queries to Phloem, we can look into the data and ask these types of questions.

As well, Phloem can facilitate more complex custom queries, such as what was in the subject's field of view at any time throughout the experience. For example, we may want to know if a participant observed a particular object of interest, such as a roof guard, so that we can compare this sighting to whether or not the guard was reported in the Immediate and Delayed Memory assessment. As not every participant has the same experience in the outside epoch of *DarkCon* this is especially important. We do not want to score as wrong a missed report of an object that was not even seen. For example a Phloem query can account for how long the sentry on the roof (or any object) was within the field of view (FOV) of the participant. We can assume that if the object was in that FOV for a certain number of seconds, the chances that the participant perceived the object are very good (Although "seeing" and "perceiving" cannot ultimately be deemed as equivalent!). Having this capability allowed us to correlate specific behavioral activity with the physiological data being captured throughout, as well as with participant data from the self report questionnaires. Phloem allowed us to account for individual differences in the free will experience that might not have been possible otherwise and it is possible to customize any queries that make sense for any particular study.

4.2   Detailing a participant's physiological response

Phloem allows for a detailed analysis of an individual's unique experience in a VE. To illustrate this, we will present one subject's experience via his recorded skin conductance response, as displayed in Figure 3.
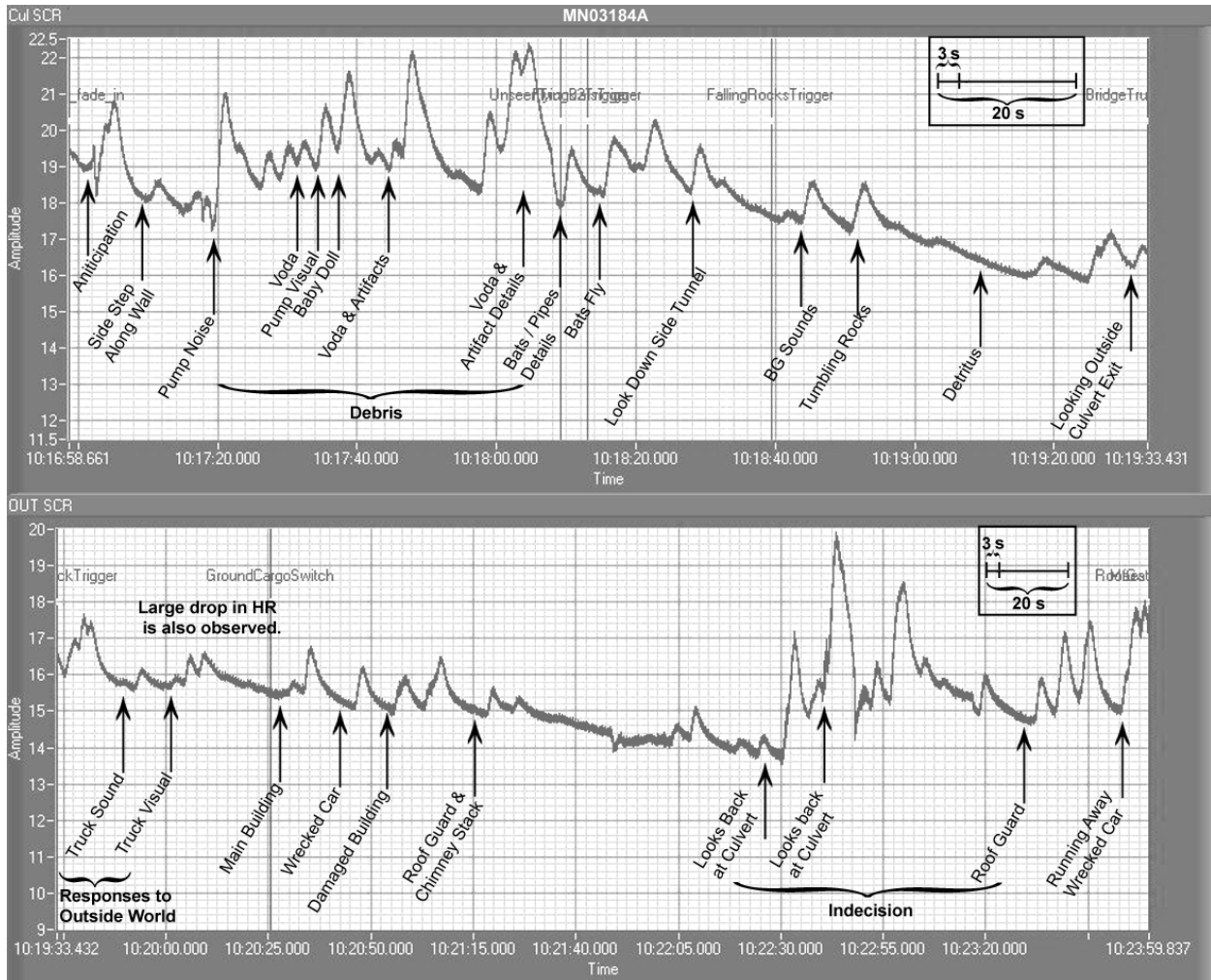
Figure 3. Annotated Skin Conductance results from one DarkCon subject obtained via a replaying of the experience with Phloem

With SCR, both the onset of a stimulus-related response (i.e. the SCR latency), and the rise time (between onset and peak) are typically between 1 and 3 seconds. For this reason a time scale of 20s with a minor of 3s is displayed to help read the annotated SCR graphs corresponding to the time spent inside the culvert (154.8s) and outside the culvert (266.4s) before this particular subject was detected by the roof guard/sentry. The unit for the SCR is 10mV/µS, which is the gain used for this subject. On the vertical axis 1 unit = 0.1µS.

The first large SCR signal displays an anticipatory response, *i.e.* the subject had just started out in the dark tunnel, and was looking ahead. He sidestepped and walked along the wall towards the red glow of an alcove containing a pump, which was heard but not seen. Just as the participant reached the alcove, he turned his gaze to his right and down, noticing debris (in this case, a water carrier labeled *Voda*). After a turn he finally made a visual contact with the pump, then looking back over to his left and down he noticed a baby doll in the mud. Note that when the participant looked at details (Voda and the debris) strong SCRs were elicited. The participant then moved on towards overhanging pipes and looked more closely at the pipes and bats hanging from them. A response from the bats flying away is observed (which we designed as a startle stimulus). As he continued down the side tunnel another response is observed. The participant saw and heard stones rolling down a small dirt mound while hearing a distant (truck) rumble, which produced two clear SCRs.

At the culvert exit, but before leaving its "safe" confines, the participant looked outside (left and right), with an observable small cluster of SCRs and simultaneously had a pronounced drop in HR that is not shown on this chart. This HR deceleration might reflect an attentional orientation of the participant to the novel environment of the outside world. At the exit of the culvert, a loud truck was first heard, and then seen, with the subject's gaze

traveling upwards to an overhanging bridge, bringing the large truck into visual contact – both stimuli producing small responses. It is interesting to observe the responses when the main building, the wrecked car, and the damaged building are seen. Of great interest to our study is the subject's response when he first saw the lookout guard on the rooftop. It seems that there was a slight confusion in deciding where to go next and the greatest response appeared when the subject looked back at the culvert entrance. Did he feel exposed now to more imminent danger? Was he searching for a place to hide? A little later, this subject saw the roof guard again, and reacted by running for cover behind a wrecked car (placed there for exactly this purpose). At that point he was detected, and the end of the scenario was played. In this case the scenario was ended with a dog attack. Overall, this subject's SCR indicates responses at many of our purposely placed emotional hotspots.

Both HR and SCR data were derived over the three time epochs defined earlier and reported in terms of mean, median, and standard deviation values. In the case of the SCR, averaging the SCR data points over the epoch of choice derived a crude estimate of the SCR mean level. Figure 3 illustrates how a replay of the VR experiment helps produce an overall view of the reactions, which shows a wealth of event related response. We also plan to include the quantitative information contained in the SCR that is not yet shown here. In this regard, a more detailed analysis of the SCR is currently underway to score the amplitude and latency for each non-specific response using a parameterization software package (EDR_PARA, Version 3.73) by German researcher Florian Schaefer. This will allow us to report the sum of amplitude (for instance, exceeding a 0.15 µS level) and the frequency of non-specific responses for all three epochs. Note that once edited, this list of non-specific response parameters also permits us to look at singular events with a smaller time epoch, such as when the user disturbs a flock of bats that abruptly fly away (i.e. a startle stimulus).

A comprehensive statistical analysis of derived data, is currently in process. This will help us to further determine the relationship between subject characteristics, physiological arousal, behavior and the memory data of the participants in this initial study and is expected to be completed in June 2005.

5 Conclusions and Future Work

Just as in the naturalistic exploration of real world environments, humans who experience free will exploration of virtual environments demonstrate a wide range of behaviors and responses. This is to be expected. It is precisely these individual manifestations of behaviors and responses within a virtual environment that is of most interest to our research. Although this poses certain methodological challenges that go beyond what is typically found in traditional stimulus/response studies, it is exactly this agency that can be one of the assets that VR offers human research. The information that can be extracted and visualized via Phloem is invaluable in this regard and may offer a more precise approach to quantifying naturalistic behaviour in a VE. We eventually expect that with a large enough subject population, to be able to extract and quantify typical patterns of behavior within such free agency worlds. In addition to expanding the library of custom queries generated over time with this application, we plan to enhance Phloem by providing the evaluator or analyst additional tools to build and graph queries on the fly during real time VE interaction from the Phloem interface. This will allow for exploration of participants' data in a highly interactive, immediate and usable fashion. We believe that continued work in this area will result in even more robust tools to effectively manage and analyse the complex streams of data that are possible when research questions dictate a free will interaction format within VR studies.

Figure 4. Scenes from the Virtual Iraq exposure therapy application for combat-related PTSD

For example, Phloem will be integrated into an ongoing clinical application project that is targeting the treatment of Post Traumatic Stress Disorder in returning Iraq and Afghanistan military personnel (Rizzo et al., 2005). In this application, designed to deliver graduated exposure therapy within the context of VR scenarios that resemble combat-related settings (see Figure 4), clinicians have the capacity to deliver real time trigger stimuli while monitoring the ongoing physiological status of the client on the same interface. This integrated interface and data

capture approach is essential for giving the clinician the capacity to modulate client anxiety responses, as is essential to promote the therapeutic habituation that is desired within an exposure therapy format. Since this PTSD application is necessarily a free will exploratory environment, Phloem will be an essential tool for developing a "fine-grain" analysis of the psychophysiological factors that underlie this disorder in order to design more effective treatment protocols. As we begin to integrate Phloem into other such applications and share the tool with other researchers, we expect its functionality to evolve and more comprehensively address such free will VR research methodology challenges. The SEE Project is at the beginning of this long term research program and we anticipate that the Phloem tool will be of benefit to the many in the community of VR researchers and clinicians.

6   Acknowledgement

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