Using Biometrics to Evaluate the Efficacy of Virtual Reality Learning Environments Through the Detection of Awe

Christopher Yockey
Air University eSchool
Maxwell AFB, AL
Christopher.yockey@us.af.mil

ABSTRACT

Can a cartoon make you cry? Can it make you feel empathy? Until recently, my answer, apart from a certain Pixar movie about a widower and his balloons, would have been a resounding no. Then I witnessed a demonstration of a virtual training technology that changed my perception. I realized that virtual environments don't have to be completely life-like to be immersive. As virtual reality (VR) equipment costs have decreased, it has found many uses, especially in education and training. VR is effective in a wide variety of applications because of its ability to immerse users in relevant environments. Each application is unique and requires a different level of realism to be effective. Most organizations that want to use VR for education and training don't have large budgets to develop virtual environments, so the question becomes, how can a designer determine when their virtual environment is realistic enough?

The traditional way of evaluating virtual environments is to have users test them and report on the experience. This method can provide useful feedback, but it results in subjective answers that may not reflect the ability of the environment to promote learning. Advances in biometric sensors have made it possible to monitor a user's physiological responses while using a VR system. This paper explores the possibility of using biometric data to objectively assess a virtual reality learning environment's ability to encourage positive learning outcomes. First, it discusses the importance of immersion and presence in learning. Next, it provides an overview of several biometric measures and what they indicate about the autonomic nervous system. The paper then explores the awe effect and how it can be measured using biometrics. It then examines how experiencing awe leads to improved learning outcomes. Finally, the paper discusses the application of this evaluation method to the design of virtual reality learning environments.

ABOUT THE AUTHOR

Christopher Yockey is a Weapons Integration Engineering Flight Chief for the United States Air Force. He earned a Bachelor's Degree in Aerospace Engineering from Iowa State University and a Master's Degree through the Air Command and Staff College Online Master's Program. In his 14 years as a developmental test engineer, he has served as a datalinks engineer, electronic warfare engineer, and project engineer testing the F-16, F-35, and RQ-4, as well as serving a career-broadening assignment as a program manager.

Using Biometrics to Evaluate the Efficacy of Virtual Reality Learning Environments Through the Detection of Awe

Christopher Yockey
Air University eSchool
Maxwell AFB, AL
Christopher.yockey@us.af.mil

INTRODUCTION

Can a cartoon make you cry? Can it make you feel empathy? Until recently, my answer, apart from a certain Pixar movie about a widower and his balloons, would have been a resounding no. Then I witnessed a demonstration of the Emotional Intelligence Institute's training technology (Emotional Intelligence Institute, n.d.). At first, the avatar in the training scenario looked very cartoonish, and I wasn't sure how effective the training would be. However, a few minutes into the training scenario, I was completely engaged with the avatar and felt empathy for its difficult emotional state. I wanted to find a way to help the avatar just as if she were a real person asking for help. As I reflected on what I had just experienced, it struck me that I was completely immersed in the training scenario even though the graphics made the avatar look more like a cartoon than a real person. I realized that a virtual environment (VE) doesn't have to be completely life-like to provide an immersive experience. Hale et al. (2014) suggest that the necessary level of realism in a VE depends on the intended application and that setting the level of realism correctly is a significant challenge that designers of VEs must overcome. The goal should be for a designer to create a VE that meets the intended purpose with the least expenditure of resources.

The challenge of determining the proper level of realism applies to all designers of VEs, but it is especially important for designers of virtual reality (VR) environments. One of the significant advantages of VR is the ability to immerse users in virtual worlds with 360-degree views. The added complexity of VR environments (VRE) compared to two-dimensional VEs means that misjudging the required level of realism could add significant effort and cost to developing the environment. Devoting extra time and money to developing a VRE that is overly realistic is wasteful for any application but could be incredibly detrimental to applications for educational institutions. Whereas video game companies may have large budgets for game development, educational institutions typically do not have large budgets, and wasted funds can hinder their ability to fulfill their mission.

Understanding the challenge and its importance, the question becomes how to determine the proper level of realism during the development of a VRE. The traditional method of evaluating VEs is for users to test them and then report on their experiences, usually in a survey. Unfortunately, this method has several shortcomings. For example, it requires a user to think about the experience while using the environment, which can be distracting and may provide incomplete data on some aspects of the environment (Hale et al., 2014). Surveys measure perceptions, not facts; by their nature, they provide subjective observations. (Glass & Sue, 2008; Hale et al., 2014). In addition to these issues, surveys can give inconsistent results, making it difficult to reach a conclusion. Wikman (2006) presents evidence that survey results may not always reflect respondents' true feelings. This can be seen when answers to similar questions on the same survey have very different responses or when respondents give different answers when asked the same question at a later time. Designers need a method to objectively assess a VEs ability to fulfill its purpose. Advances in biometric sensors have made it possible to monitor a user's physiological responses while using a VR system. By measuring and correctly interpreting biometric data, designers can objectively evaluate their VRE's ability to encourage positive learning outcomes.

BACKGROUND

As equipment costs have decreased, VR has found many uses, especially in education and training. The Air Force has used VR in such varied applications as training aircraft ground crews proper maintenance procedures and teaching new pilots how to fly. Using VR to provide immersive experiences has resulted in better training outcomes in less time than traditional methods (Sampson, 2022; Cohen, 2021). The increased use of VR for education has made the need for an objective evaluation system acute. When developing VREs for education, designers need to make the environment realistic enough to take advantage of the benefits of VR without incurring unnecessary costs. Achieving this balance is crucial for VR to continue its growth in education and training. If the VRE does not promote increased learning or is too expensive, institutions with limited budgets will not continue to fund the use of VR systems. The development and implementation of an objective evaluation system to support designers in this task are essential. A biometric-based system that can detect learning in students using VR systems would fit this role and provide designers the feedback they need to achieve the proper balance between realism and cost.

IMPORTANCE OF VIRTUAL REALITY FOR LEARNING

VREs focused on learning can be called virtual reality learning environments (VRLE). Before a method to evaluate a VRLE's impact on learning can be created, it is necessary to understand how VRLEs affect the process of learning. The fundamental attributes of VRLEs that affect learning are their ability to create a sense of immersion and presence. These attributes are closely related but distinctly different and must be understood before proceeding.

Immersion

One of the essential aspects of VRLEs is the ability to immerse users in an environment conducive to the desired learning objectives. Therefore, the level of immersion is critical to the design of a VRLE. For this paper, immersion is defined as a psychological state where the user feels as if they are surrounded by and a part of the virtual environment, able to interact with its various components and see appropriate reactions that match their expectations (Greenwood-Ericksen, Kennedy, & Stafford, 2014; Soliman et al., 2021). This definition purposefully did not include a description of any hardware or any minimum level of graphics, choosing instead to focus on how the user feels about the experience. A VRLE does not have to be photo-realistic to be immersive; it could even be obviously computer-generated if it creates the required level of immersion for a given objective. (Soliman et al., 2021; Hale et al., 2014). While initially counter-intuitive, this should not come as a surprise to anyone who has ever been engrossed in a movie or novel when some noise or movement in their peripheral vision snapped them out of their focused state, and they realized they weren't taking part in the story. Even though they weren't using immersive technology like a VR headset, they were immersed in the movie or novel. Immersion is widely believed to contribute to increased levels of presence, another important term when discussing VRLEs (Wu, Yu, & Gu, 2020).

Presence

Presence is defined as a psychological state where a user forgets that they are experiencing a synthetic environment and believes they are really present in that environment (International Society for Presence Research, 2000). When applied to VRLEs, this means a user feels like they are present in the VRLE they are using, not just viewing the environment. Presence is a perception that can vary across users. Different users may experience different levels of presence while using the same environment. The perception of presence can also vary in degree; it is not an on or off perception. Many factors affect a user's perception of presence, but generally, the more a user can forget that they are using technology to provide the immersive experience, the higher the level of presence (International Society for Presence Research, 2000). Now that immersion and presence have been defined, it is possible to explore how they impact the ability of a user to learn.

Benefits of Immersion and Presence to Learning

The use of immersive VRLEs has been shown to have benefits to learning, including increased knowledge transfer and skill development, compared to traditional lecture-based learning, especially in science, technology, engineering, and math (STEM) education (Wu, Yu, & Gu, 2020; Hu-Au & Lee, 2017; Soliman et al., 2021). This section explores some of the reasons why VRLEs benefit learning.

When a user is sufficiently immersed in a VRLE that they experience a sense of presence, they become more engaged with the learning experience and switch from passive to active learning (Hu-Au & Lee, 2017; Soliman et al., 2021). The increased engagement helps students absorb new information by building off existing knowledge and creating personal connections to the topic, which contributes to intrinsic motivation (Cornell University, n.d.).

Immersion also contributes to positive attitudes towards the subjects and positive student perceptions about learning (Wu, Yu, & Gu, 2020). The ability to engender interest and a desire to learn are extremely valuable to educators. Once a student becomes intrinsically motivated to learn, the educator's task becomes much easier.

In an immersive environment, the user no longer notices the interface between themself and the environment, and artificial barriers between the information and the user no longer exist (Winn, 1993). This means that a user experiences the environment and obtains the desired information naturally, rather than reading about it or being told about it. This enables what Winn (1993) called "non-symbolic interaction" (pp. 3-4) with the environment, where a user doesn't have to learn the syntax or symbology before they can learn concepts of the subject. They can simply experience them by interacting with objects in the VRLE just as they would in the real world. These interactions enable users to experience concrete learning and gain the type of first-person knowledge typically only achieved through direct, hands-on experiences in the real world (Hu-Au & Lee, 2017; Winn, 1993; Wu, Yu, & Gu, 2020).

The ability to immerse users in almost any environment creates many opportunities for learning experiences. The sense of presence created through immersion allows users to suspend disbelief and feel like they are in an environment that would be impossible to visit in real life. It also enables virtual field trips to any location or time period. Experiencing historical events rather than just reading or hearing about them creates a personal experience that results in increased retention of information (Hu-Au & Lee, 2017). The sense of presence can also create genuine feelings of identity or empathy by enabling users to experience what it is like to be someone else. (Wu, Yu, & Gu, 2020). The ability to experience being someone else provides powerful opportunities to understand different perspectives, such as being an elderly person or living in a refugee camp (Hu-Au & Lee, 2017). It is easy for students to ignore or place little interest in issues that don't have a personal impact but experiencing what others go through in a VRLE makes it personal. Now that the importance of immersion and presence to the effectiveness of VRLEs has been established, the question of determining when a VRLE is immersive enough to establish a sense of presence in a user and enable positive learning outcomes must be addressed. To provide an objective evaluation using biometrics, the first step is understanding what biometric measures can be obtained while using a VR system.

BIOMETRICS

Biometrics, in the sense that this paper uses the term, is the collection and analysis of biological data to determine something about the physiological state of a subject (Collins, n.d.). The biometric measures used in the proposed evaluation of VRLEs are measures of functions controlled by the autonomic nervous system (ANS).

Overview of the Autonomic Nervous System

The ANS, sometimes referred to as the involuntary nervous system, operates without the need for conscious control (McCorry, 2007). The primary purpose of the ANS is to maintain a consistent bodily environment, known as homeostasis, despite any internal or external factors that may perturb the system. The ANS regulates many critical bodily functions such as heart rate, blood pressure, body temperature, digestion, and sweating (Andreassi, 2000; McCorry, 2007). The ANS is divided into the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). The SNS is activated in high-stress situations that trigger a fight-or-flight response. SNS-controlled reactions include increased heart rate, blood pressure, and sweating. The PNS restores normal bodily function and is activated in situations of rest and relaxation. PNS-controlled reactions include decreases in heart rate and blood pressure. The ANS and PNS work together to control body functions and enable smooth transitions between states of high activation and normal functioning. One system will be dominant depending on the situation, and as one system is in activation, the other is typically in withdrawal (Andreassi, 2000; McCorry, 2007). Interpreting the current state of the ANS and whether the SNS or PNS is dominant provides indications of the current cognitive state. The measures that will be used to give these indications are discussed below.

Electrodermal Activity

Electrodermal activity (EDA), sometimes referred to as galvanic skin response (GSR), is a measure of the skin's electrical conductivity. The level of conductivity indicates the level of sympathetic activation (Shan & Mason, 2016). Changes in EDA are related to the activity of eccrine sweat glands, which are located in most areas of the skin but are most highly concentrated on the palms of the hands and the soles of the feet. The eccrine glands on the palms and fingers have a weak response to temperature but a strong response to psychological and sensory stimuli. In contrast, eccrine glands in other areas, such as the forehead and neck, have a strong response to temperature and a weak response to psychological or sensory stimuli (Andreassi, 2000; Dawson, Schell, & Filion, 2017). The SNS innervates eccrine sweat glands; therefore, sweating is controlled through sympathetic activation. Sweating in response to psychological and sensory stimuli may be an evolutionary tactic that is part of the fight-or-flight response. It is theorized that increased sweating may improve grip and protect the skin from injury. Experiencing clammy hands in situations of fear or anxiety are examples of this reaction (Andreassi, 2000; Dawson, Schell, & Filion, 2017).

Interestingly, it isn't necessarily the amount of sweat on the skin's surface that affects EDA. This is evidenced by the fact that changes in EDA can be detected before sweat appears on the skin's surface (Darrow, 1927, as cited in Dawson, Schell & Filion, 2017). Dawson, Schell, & Filion (2017) proposed a model where the sweat ducts that connect the eccrine glands to the surface act as a set of variable resistors. The stronger the sympathetic activation, the more sweat fills up the ducts, creating a more conductive path through the corneum layer of skin. This makes sense as there is a strong correlation between the strength of a sympathetic reaction and skin conductance. (Andreassi, 2000; Dawson, Schell, & Filion, 2017). EDA has two components, skin conductance level (SCL) and skin conductance response (SCR).

SCL is a measure of the tonic level of EDA, which is the relatively stable level of EDA over time. SCL typically changes slowly and increases or decreases with the level of sympathetic activation. SCL typically decreases when a subject is resting, indicating a sympathetic withdrawal. It will rise when the subject is exposed to a stimulus, indicating a sympathetic activation, before gradually decreasing again. There can be large variations in SCL between subjects and even between the same subject in different psychological states, but a normal range is 2 to 20 micro-Siemens (Dawson, Schell, & Filion, 2017).

An SCR is a measure of the phasic level of EDA. They indicate a rapid increase in EDA that is very noticeable and looks like a spike when EDA is plotted vs. time (Andreassi, 2000). There is no specific definition of what qualifies as an SCR, but a minimum change of 0.01 to 0.05 micro-Siemens is typically considered an SCR. There are two types of SCRs, specific SCRs, and non-specific SCRs (NS-SCR). Specific SCRs are tied to some stimulating event and usually occur within 1 to 4 seconds of the stimulus, whereas NS-SCRs are not linked to any particular stimuli (Andreassi, 2000; Dawson, Schell, & Filion, 2017). The magnitude of an SCR is normally 0.1 to 1.0 micro-Siemens, and the strength of the SCR is correlated to the level of sympathetic activation. The significance of an SCR is determined by comparing its detection to the presented stimuli. NS-SCRs can also be an important measure. An average rate of NS-SCRs is 1 to 3 per minute while resting, and an increased level of NS-SCRs can indicate sympathetic activation. (Dawson, Schell, & Filion, 2017). Figure 1 shows example plots of EDA data. The top box shows the as-measured EDA data, while the middle and bottom boxes show the SCR and SCL components of EDA broken out after processing. Note each SCR's rapid rise and fall and the much more gradual rise in SCL.

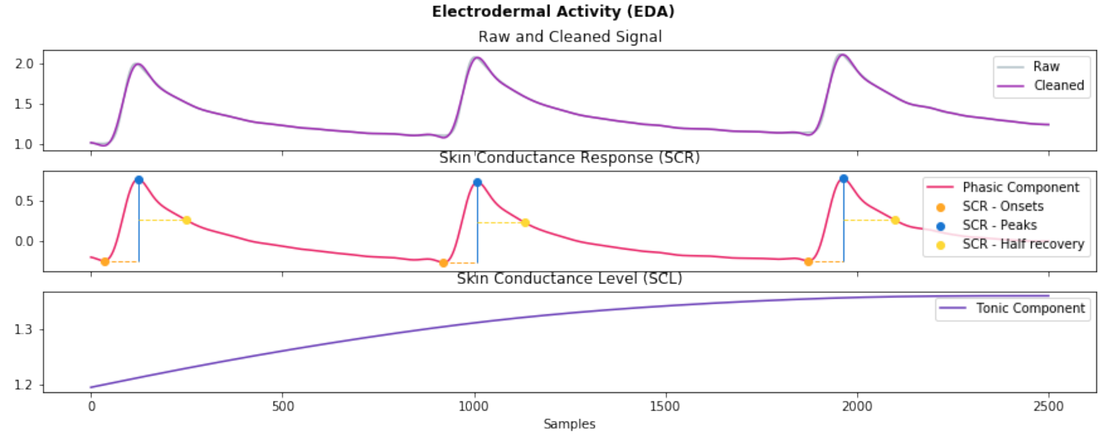

Figure 1. Example Plots of EDA (Makowski, 2020)

Heart Rate Variability

Heart rate variability (HRV) is an essential biometric measure in evaluating VRLEs because it can indicate relative levels of SNS and PNS activation (Shan & Mason, 2016). HRV is a measure of the change in interbeat interval (IBI) which is the time between heartbeats (Shaffer & Ginsberg, 2017). HRV can be analyzed in the frequency domain by using Fast Fourier Transforms (FFT) to break the HRV data into three frequency bands. The three frequency bands are defined as very-low-frequency (VLF) ≤ 0.04 Hz, low-frequency (LF) 0.04 – 0.15 Hz, and high-frequency (HF) 0.15-0.4 Hz (Camm et al.,1996).

The source of VLF band power is not as well understood as the other frequency bands. There is evidence that the heart's intrinsic nervous system sets the VLF rhythm, and the amplitude and frequency of the oscillations are controlled by SNS activity, indicating that increases in VLF power may be related to SNS activation (Shaffer, McCraty, & Zerr, 2014). Both the PNS and SNS can contribute to the power of the LF band. The PNS is the sole contributor to the power of the HF band, making it a good indicator of parasympathetic activation. The ratio of LF power to HF power can indicate the ratio of SNS and PNS activity. A low LF to HF ratio indicates parasympathetic preeminence, while a high LF to HF ratio indicates sympathetic preeminence (Shaffer & Ginsberg, 2017). The design of the VRLE must be considered when using LF to HF ratios to determine the ratio of SNS to PNS activity. If the VRLE doesn't involve any physical activity or other stress that would cause SNS activation, the LF to HF ratio could give misleading results because the LF power would all be from the PNS. (Shaffer & Ginsberg, 2017).

Measuring ANS Responses While Using a VRLE

The ability to measure ANS responses provides insight into a subject's cognitive state, which is valuable for evaluating VRLEs. There are traditional lab-based methods of measuring ANS response using sensitive, finger-mounted electrodes to measure EDA and an electrocardiogram (ECG) to measure HRV. Although the lab-based methods provide very accurate data, those methods are not practical when a subject is using a VRLE due to the required placement of sensors that restrict the use of the hands and wires that restrict body movement. Luckily, there are technological solutions in the form of wrist-mounted sensors that can provide reliable measures of ANS responses without restricting a user's freedom of movement.

One example is the Empatica E4 Wristband which is a medically certified, unobtrusive sensor package about the size of a wristwatch that includes an EDA sensor, a photoplethysmography (PPG) sensor, a 3-axis accelerometer, and a temperature sensor that is capable of 32 hours of continuous measurements (see Figure 2). The device is worn on the wrist and is capable of onboard recording or real-time streaming via Bluetooth (E4 Wristband User's Manual, 2020). A study by Sagl et al. (2019) compared the Empatica E4 to a laboratory-grade EDA measurement device that used traditional electrode placement while participants were pedaling a stationary bike. They found that the E4 provided EDA measurements that were reasonably similar to the laboratory-grade device. Additionally, the Empatica E4 has been successfully used in numerous studies to measure EDA (Birenboim et al., 2019; López-Carral et al., 2022; Maier et al., 2019; Yates et al., 2017). The PPG sensor included on the Empatica E4 captures blood volume pulse (BVP) data that can be used to calculate HRV. HRV calculated from PPG-based measurements has been shown to be accurate within 6% of ECG-based measurements (Shaffer & Ginsberg, 2017). Although the Empatica E4 doesn't provide the same level of fidelity as lab-based methods, the study comparing it to traditional measurement methods, along with the fact that it has been successfully used in multiple studies, indicate it is a good candidate for collecting EDA and HRV data to evaluate VRLEs.

Figure 2. Empatica E4 Wristband (E4 Wristband Factsheet, 2020)

CORRELATING BIOMETRICS TO COGNITIVE STATE

There are multiple ways that biometrics could be used to determine if a user is learning while using a VRLE. Some studies have suggested using EDA to measure arousal as a correlate of interest (Hardy et al., 2013). Other studies have suggested using changes in heart rate to detect the processing of new information (Andreassi, 2000). Still, others have suggested using EDA and heart rate to determine the affective state of a user (McQuiggan, Lee, & Lester, 2006, Yates et al., 2017). While these studies propose interesting options worthy of further investigation, this paper focuses on using biometrics to detect awe, which, as will be discussed later, positively impacts learning outcomes. The decision to focus on detecting awe was due to the natural relationship between awe and VREs. The sense of immersion and presence that VR can induce is capable of producing intense feelings of awe (Chirico et al., 2016; Chirico et al., 2017). Designers can take advantage of the inherent capabilities of VR systems to create VRLEs with awe-inducing experiences that will feel natural to users.

Awe Effect

Awe is a complex emotion that is not as well understood as other emotions and has only been studied empirically for the last 20 years (Chirico et al., 2016; Chirico et al., 2017; Keltner & Haidt, 2003; Shiota, Keltner, & Mossman, 2007;). Keltner & Haidt (2003) were among the first to approach awe from a psychological point of view and defined it as being comprised of two components: perceived vastness and the need for accommodation. Feelings of perceptual vastness can be caused by many things ranging from viewing natural wonders to seeing inspirational leaders. While the source of the perceived vastness can vary, to be awe-inducing, it must expand the observer's frame of reference. Whatever the stimulus, it must be so far outside the observer's experience that it can't be assimilated into current schemas. It must drive the change of existing schemas or the creation of entirely new ones in a process known as accommodation. This process can be reflected by feelings of confusion, surprise, or wonder as well as difficulty comprehending what one is seeing (Keltner & Haidt, 2003; Shiota, 2007). According to Keltner & Haidt's definition, an experience must have both perceived vastness and accommodation to be considered awe; if it exhibits only one, it is not truly an awe experience. There are many different types of awe experiences, some of which have positive valence and some of which have negative valence. The type of experience is driven by the perceived vastness, which can have aspects of threat, beauty, ability, virtue, or the supernatural (Chirico et al., 2017; Keltner & Haidt, 2003).

Awe experiences can have huge effects on those that experience them and, in some cases, may even be life changing (Keltner & Haidt, 2003). Awe changes how people think about themselves and the world around them. It changes their focus from their own personal needs and desires to the outside world. Put another way, someone experiencing awe is likely to be more aware of their surroundings and less aware of themselves (Shiota, Keltner, & Mossman, 2007). The overview effect experienced by many astronauts is an excellent example of an awe experience. The overview effect is a profound reaction frequently experienced by astronauts viewing the Earth while in space. Many astronauts report intense feelings of awe, and some are overcome with such emotion that it causes them to view themselves and our planet differently (Yaden et al., 2016). An interesting feature of the overview effect is that the perceived vastness experienced by astronauts could be both perceptual and conceptual. Viewing the beauty of the Earth could be perceptual, just like viewing any natural wonder. However, seeing the whole planet at once and considering that everything meaningful in life is there or even just viewing familiar features from a different perspective could be conceptual (Yaden et al., 2016). Powerful emotions such as awe can have effects that extend beyond the psychological and into the physiological. These links between psychological and physiological states are the key to using biometrics to detect awe experiences.

Awe and the Autonomic Nervous System

By examining ANS responses through the analysis of biometric data, it is possible to determine whether or not a user of a VRLE experienced a state of awe. An empirical study by Shiota et al. (2011) showed that it was possible to differentiate between five different emotional states based on differences in ANS responses. They found that when study participants were exposed to two-dimensional video stimuli, it resulted in a unique biometric response for each emotion. When subjects were exposed to awe-inducing stimuli, they demonstrated a lengthened cardiac pre-ejection period (PEP) and a decrease in EDA in the form of a decreased SCR count and SCL, all of which are signs of sympathetic withdrawal. Chirico et al. (2017) expanded on the work of Shiota et al. by further investigating the links between ANS response and awe, adding the investigation of parasympathetic response and including immersive 360-degree videos as a stimulus. They measured EDA and BVP while the study participants watched neutral and awe-inducing videos on a two-dimensional screen and in an immersive 360-degree environment. SCRs were counted in the same manner as the Shiota et al. study. The BVP data was used to compute HRV, which was analyzed in the frequency domain to determine ANS response by examining VLF and HF power for each stimulus. The results showed that awe caused a sympathetic withdrawal and parasympathetic activation, which agrees with and expands on Shiota et al. (2011).

Chirico et al. (2017) also found interesting results regarding using immersive video to stimulate awe. It was discovered that SCR counts and VLF power were significantly higher for the immersive environment regardless of content, demonstrating that immersive environments are capable of causing sympathetic activation. However, when awe-inducing content was viewed on the immersive display, a sympathetic withdrawal and a strong parasympathetic activation were recorded. These results point to the potential of VREs to induce strong emotional responses and confirm the link between parasympathetic activation and awe.

The Shiota et al. and Chirico et al. studies show that different ways of measuring biometrics can provide the data necessary to determine if users experience awe. Where Shiota et al. used a lengthened PEP and decreased EDA to indicate a sympathetic withdrawal, Chirico et al. used HRV derived from measured BVP data to indicate sympathetic withdrawal and parasympathetic activation. The importance here is that EDA and BVP data can be measured using the Empatica E4 described earlier. The ability to use a single, unobtrusive, wrist-mounted sensor to collect all the necessary data to determine if a user experienced awe while using a VRLE is incredible. It gives designers a practical, reliable way to collect data to evaluate their environments.

EFFECT OF AWE ON LEARNING

As stated previously, awe is a complex and powerful emotion that can have profound and sometimes long-lasting effects on those who experience it. One of those effects is improved learning during experiences of awe. This section will explore the reasons behind awe's ability to enhance learning to extract lessons that can be used in the design of VRLEs.

Positive affect is believed to improve learning and knowledge retention (Coles, 1999; King et al., 2015). Although awe is a complex emotion that can have positive or negative valence (Keltner & Haidt, 2003), it is generally regarded as a positive emotion (Shiota, Keltner, & Mossman, 2007; Shiota et al., 2017). Upon first inspection, it seems that perhaps awe fits into this schema and only improves learning because it causes a positive affect in those who experience it. Rudd, Hildebrand, & Vohs (2018) addressed this in a series of eight experiments investigating the link between awe and openness to learning. They found that people experiencing awe, induced in natural and lab settings, were more likely to be interested in learning than those in a neutral state. They also compared awe to other positive emotions and found that interest in learning was not just caused by a positive affect or an aroused state. Finally, they discovered that the increased interest in learning was not due to a boost in general motivation. The results of their experiments indicate that the links between awe and improved learning are as complex as the emotion itself and require a detailed exploration.

Accommodation

Awe is classified as one of the epistemic emotions, which are emotions that are related to knowledge and understanding. What differentiates awe from other epistemic emotions, such as curiosity, confusion, and surprise, is the need for accommodation (Valdesolo, Shtulman, & Baron, 2017). Remember that according to Keltner & Haidt (2003), a true awe experience must have the two components of perceived vastness and accommodation. The perception of vastness causes a violation of expectations that disrupts existing schemas and creates feelings of uncertainty and confusion. These feelings motivate people to seek out new information in an attempt to understand the experience and thereby achieve accommodation. This need for accommodation increases the willingness and desire to learn, which is one of the primary methods by which experiences of awe improve learning (Cuzzolino, 2019; Rudd, Hildebrand, & Vohs, 2018; Valdesolo, Shtulman, & Baron, 2017; van Limpt-Broers, Lowerese, & Postma, 2020). While it is true that awe increases willingness and desire to learn in general, the need for accommodation can have a focusing effect that draws attention to the experience that needs to be understood (Price et al., 2021). This has important implications for the design of how awe is incorporated in VRLEs. If done correctly, the use of awe can have an amplifying effect on the desired learning objectives, but if done improperly, some of the benefits of using awe in VRLEs will be lost.

Violating expectations can also lead to an increase in causal reasoning to determine the cause of the violation. Children exhibit a large increase in this reasoning and tend to look deeper to understand the situation that led to the violation. Children will not only suggest possible explanations but also look for information to confirm they have the correct explanation (Valdesolo, Shtulman, & Baron, 2017). This opens the opportunity to use awe to get students interested in a portion of a subject and then, through the natural exploration that occurs through the accommodation process, expand the interest to the rest of the lesson. For example, a lesson about the impact of garbage pollution in the ocean could induce awe by showing the size of the Great Pacific Garbage Patch (GPGP) (National Geographic, n.d.). As the students try to understand how the GPGP became so large as part of the accommodation process, the lesson could shift and describe the impact of pollution on marine wildlife and how that can impact the human food chain. Using awe in science education could be particularly beneficial. There are many areas of study in science that will produce violations of expectations because the processes behind easily observed but hard-to-explain phenomena can't be assimilated into deeply held but incorrect intuitive theories (Valdesolo, Shtulman, & Baron, 2017).

The ability of awe experiences to change how one views the world can have long-lasting impacts beyond the immediate experience and lead to life-long changes in tendencies (Price et al., 2021). Consider the example of the GPGP. After the students learn about the GPGP and the effects of pollution on marine wildlife and the human food chain, if the lesson then covers the importance of recycling and reducing the amount of single-use plastic thrown away, students will likely remember those key points. If the awe experience was strong enough, it could influence those students to make everyday changes like putting plastic bottles in the recycle bin instead of the trash can.

Effect on Use of Heuristics and Existing Knowledge

Most positive emotions result in the use of heuristics or existing knowledge structures to interpret new events. However, awe, even when it has a positive valence, has the opposite effect. When experiencing a state of awe, people rely less on heuristics and carefully evaluate new information (Griskevicius, Shiota, & Neufeld, 2010). Experiencing awe can also result in noticing and remembering more details of an experience rather than inserting erroneous details from typical experiences. This occurs because awe suppresses the normal expectations which experiences are filtered through and increases attention to detail. This effect may be moderated by the strength of the awe experience (Danvers & Shiota, 2017). Put another way, the stronger the feeling of awe, the more details that will be retained. Interestingly, Danvers and Shiota (2017) found that all types of awe – awe blended with fear, awe blended with admiration, and prototypical awe - result in reduced use of heuristics and existing knowledge compared to a neutral condition or other positive emotions. This opens the possibility of using many different sources of awe when designing VRLEs, potentially even those with a negative valence. Hicks & Stewart (2020) suggest that it doesn't matter if the awe-inducing experience was initially positive or negative as long as it is viewed positively after reflection. However, the author urges caution before using negatively valenced experiences and strongly suggests considering the intended audience and any unintended consequences before trying to induce awe with fear-based experiences.

Effect on Perception of Time

Awe can alter the perception of time, making people feel like they have more time available. Rudd, Vohs, & Aker (2012) compared awe to the positively valenced emotion of happiness and found that people experiencing awe felt they had more time available than those experiencing happiness. The same study confirmed that awe produced a sense of more time available, not that an abundance of time is required to experience awe. These results were affirmed in a later study by Rudd, Hildebrand, & Vohs (2018) that studied the relationship between awe, willingness to learn, and perception of time availability. In their study, Rudd, Hildebrand, & Vohs found that participants experiencing awe consistently reported feeling they had more time available than participants experiencing happiness. Rudd, Vohs & Aker (2012) propose that two existing theories, the extended-now theory and the socioemotional selectivity theory, may explain this phenomenon. The extended-now theory posits that focusing on the present elongates the perception of time such that each moment feels longer than it usually would. In an extended-now state, a person is completely focused on the present moment, and thoughts or concerns about the future become less important (Vohs & Schmeichel, 2003). The extended-now theory, combined with the fact that awe focuses attention on the present experience, could explain awe's ability to alter the perception of time (Rudd, Vohs, & Aker 2012). The socioemotional selectivity theory (SST) suggests that people are more motivated to pursue knowledge when they feel they have more time available (Carstensen, Isaacowitz, & Charles, 1999). Rudd, Vohs, & Aker (2012) extrapolate this theory to suggest that the need for accommodation may indicate that awe results in a perceived expansion of time. Taking a slightly different approach, these two theories can be combined to show that awe's ability to alter the perception of time should lead to an increased motivation to learn.

Effect of Prior Knowledge on Awe

Designing a VRLE with just the right amount of awe-inducing content is non-trivial and requires carefully thought-out details. We have seen that awe requires perceived vastness to violate expectations and start the accommodation process. This leads to the question of whether the return on investment is worth it if a particular VRLE design can only be used to induce awe once. This is actually not a problem because surprise isn't required to produce perceived vastness. Experiencing the same stimulus more than once can still induce feelings of the unknown – i.e., seeing the same natural wonder a second time may still invoke a sense of perceived vastness that leads to awe (Danvers & Shiota, 2017). In fact, Price et al. (2021) found that prior knowledge was a strong indicator of a positive awe experience and that higher levels of previous knowledge can lead to increased levels of awe. This may seem counterintuitive, but two quick examples illustrate the point. Standing on a high vantage point and looking at sweeping views of nature or a sprawling city are likely to induce perceived vastness. If you were to see this same view a week later, it would likely still induce perceived vastness. As another example, one may know that the Saturn V rocket was 281 feet tall and weighed nearly 6.5 million pounds (National Aeronautics and Space Administration, 1969), but standing at the base of one and staring up at it will most certainly induce a sense of perceived vastness that leads to awe. The more one knows about the Apollo Program and Saturn V, the stronger their sense of awe will likely be. Additionally, simply appreciating the amount of learning that is occurring can lead to feelings of awe (Price et al., 2021). Using the same VRLE multiple times and learning something new each time could be its own source of awe. While the source and intensity of an awe experience may change with the number of uses, a single VRLE can produce awe experiences several times for the same user.

APPLICATION TO DESIGN OF VIRTUAL ENVIRONMENTS

The Evaluation Process

So far, this paper has established that biometrics can indicate whether or not someone has experienced awe and that experiencing awe is beneficial to learning. Now it will discuss how to use this knowledge to evaluate a VRLE's ability to facilitate positive learning outcomes. This method is intended to be used in much the same way as the traditional method of using post-experience surveys, except that objective data will be collected while the user is experiencing the VRLE. First, a designer will build their VRLE with the goal of inducing awe while using what they feel is the minimum amount of realism to immerse the user and create a sense of presence. Next, a sample representing the intended user group's demographics and that is of sufficient size to provide statistically relevant results should be selected. Each user will be fitted with a sensor package such as the Empatica E4 and the required VR equipment. It is crucial to allow the user sufficient time to orient themselves to the feel of the equipment and to a neutral environment within the headset; anywhere from one to five minutes is typical. This ensures that measurements will reflect the stimulus of the VRLE and not just the new experience of wearing VR equipment. It also provides time to take a baseline recording with which to compare the data taken during the VRLE experience (Betella et al., 2014; Fishel, Muth, & Hoover, 2007; Hale et al., 2014; Sagle et al., 2019; Shiota, 2011). After the orientation/baseline period, the user should begin using the VRLE and complete the lesson while data is recorded.

Data Recording and Processing

The Empatica E4 is capable of recording data onboard for future download and real-time streaming via Bluetooth (E4 Wristband User's Manual, 2020). Once the data has been moved to a computer it will need to be analyzed by either commercially available or custom-built analysis tools. It is essential to time-align the data because the EDA sensor and the PPG sensor on the E4 record at different rates (E4 Wristband User's Manual, 2020), and this is likely to be the case no matter what type or brand of sensors are used. Once the data has been processed, automated tools or manual evaluation can be used to determine ANS response during the VRLE experience.

Interpreting the Results

When analyzing the data, it is important to understand that various biometric measures will respond on different timelines to the same stimulus (Hale et al., 2014). Care must be taken to correlate different biometric measurements to a specific stimulus. It was previously established that an SNS withdrawal and a PNS activation are indications of experiencing awe. If the results indicate these responses while the user was experiencing the VRLE, the user was likely in a state of awe. It will also be important to correlate the ANS reactions with events in the VRLE to ensure that the intended stimuli are inducing awe. If the results indicate that users are not experiencing awe, the designer can increase the level of realism and re-test the system. Through this iterative approach, it should be possible to identify the minimum level of realistic graphics needed to induce an awe state. It is possible that some users in the sample group will experience awe and some won't. In this case, a decision will have to be made as to whether or not enough of the sample users experienced awe to consider the VRLE good enough. There is no simple guideline for making that decision; it will have to be made holistically, considering the percentage of users that experienced awe, common demographic factors, and available budget.

The evaluation process discussed so far has been intended as a post-test evaluation. However, if the real-time streaming capability of the E4 were combined with automated real-time analysis, it would be possible to determine if a user was experiencing awe as they were using the VRLE. This could allow a designer to adjust aspects of the VRLE in real-time to see how it affects the user's awe state. Whatever analysis method is chosen, if thoughtfully designed and carefully implemented, it should provide reliable indications of a user's awe state and allow designers to develop VRLEs that induce awe with the minimum level of resources spent on realistic graphics.

CONCLUSION

As the cost of VR equipment has decreased, its popularity, especially in education and training, has increased significantly. Each application is unique and requires a different level of realism to be effective. Determining the correct level of realism to induce a sense of immersion is a significant challenge for designers as they strive to develop environments that meet the objectives of the intended application while dealing with limited budgets, especially in the areas of education and training. The ability of a VRLE to induce a sense of immersion and presence creates many opportunities for improved learning by allowing students to be a part of an environment and experience things that would otherwise be impossible. These experiences improve engagement and create personal connections that motivate students to learn. The challenge designers face is determining when an environment is realistic enough to establish the sense of immersion and presence that enables the benefits of using VRLEs.

The traditional method of using surveys to evaluate VREs is limited because of its inability to capture real-time data without interrupting the experience and the subjective nature of surveys. What designers need is an objective method to assess the ability of a VRLE to promote positive learning outcomes. By measuring and analyzing EDA and HRV, it is possible to detect ANS responses to stimuli, specifically SNS and PNS activation and withdrawal. Advances in sensor technology have made it possible to measure these biometric signals without interference while the subject is using a VR system. This technology opens the door to using biometric data to objectively evaluate VRLEs. Several evaluations can be made using biometric data, but this paper focused on the detection of awe.

Awe is a powerful emotion that involves perceived vastness and a need for accommodation. Designers can take advantage of the inherent ability of VRLEs to induce a sense of immersion and presence to create intense feelings of awe which are associated with an SNS withdrawal and PNS activation. Experiencing awe has a positive effect on learning driven by several mechanisms, including the need for accommodation, increased causal reasoning, reduced use of heuristics and existing knowledge, and altering the perception of time. These effects are not diminished when experiencing the same VRLE more than once; in fact, prior knowledge of the subject can increase the level of awe experienced.

Assuming a VRLE has been designed to induce awe, a device such as the Empatica E4 can be used to collect biometric data while users are experiencing the VRLE. By analyzing data from a representative group of users, it will be possible to determine if the VRLE succeeded in inducing feelings of awe. If the VRLE induces awe in the representative group, a reasonable assumption can be made that the VRLE will promote positive learning outcomes. The ability to objectively evaluate a VRLE using biometric data could be the key to ensuring the right balance of realism and resource expenditure that enables the continued growth of VR in education and training.

ACKNOWLEDGEMENTS

The author wishes to thank his family for allowing him the time needed to complete this paper. Without their support and understanding, this effort would not have been possible.

REFERENCES

Andreassi J. (2000). *Psychophysiology: Human Behavior & Physiological Response: Vol. Fourth edition.* Psychology Press.

Betella, A., Pacheco, D., Zucca, R., Arsiwalla, X. D., Omedas, P., Lanata, A., ... & Verschure, P. F. (2014). Interpreting psychophysiological states using unobtrusive wearable sensors in virtual reality. In *7th International Conference on Advances in Computer-Human Interactions, ACHI 2014* (pp. 331-336). International Academy, Research and Industry Association, IARIA.

Birenboim, A., Dijst, M., Scheepers, F. E., Poelman, M. P., & Helbich, M. (2019). Wearables and location tracking technologies for mental-state sensing in outdoor environments. *The Professional Geographer*, *71*(3), 449-461.

Camm, A. J., Malik, M., Bigger, J. T., Breithardt, G., Cerutti, S., Cohen, R. J., ... & Singer, D. H. (1996). Heart rate variability: standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology.

Carstensen, L. L., Isaacowitz, D. M., & Charles, S. T. (1999). Taking time seriously: A theory of socioemotional selectivity. *American psychologist*, *54*(3), 165.

Chirico, A., Yaden, D. B., Riva, G., & Gaggioli, A. (2016). The potential of virtual reality for the investigation of awe. *Frontiers in psychology*, 7, 1766. https://doi.org/10.3389/fpsyg.2016.01766

Chirico, A., Cipresso, P., Yaden, D. B., Biassoni, F., Riva, G., & Gaggioli, A. (2017). Effectiveness of immersive videos in inducing awe: an experimental study. *Scientific reports*, *7*(1), 1-11.

Cohen, R.S. (2021, Mar 23). *As Air Force revamps pilot training, flight safety concerns linger*, Air Force Times. https://www.airforcetimes.com/news/your-air-force/2021/03/24/as-air-force-revamps-pilot-training-flight-safety-concerns-linger/

Coles, G. (1999). *Reading lessons: The debate over literacy*. Macmillan.

Collins. (n.d.). Biometric. In *Collins.com dictionary*. Retrieved August 08, 2022, from https://www.collinsdictionary.com/us/dictionary/english/biometric

Cornell University Center for Teaching Innovation. (n.d.). *Active Learning*. Retrieved August 14, 2022, from https://teaching.cornell.edu/teaching-resources/active-collaborative-learning/active-learning#:~:text=Active%20learning%20methods%20ask%20students,words%20through%20writing%20and%20discussion.

Cuzzolino, M. P. (2019). *Experiences of Transformative Awe and the "Small Self" in Scientific Learning and Discovery* (Doctoral dissertation, Harvard University).

Danvers, A. F., & Shiota, M. N. (2017). Going off script: Effects of awe on memory for script-typical and-irrelevant narrative detail. *Emotion*, *17*(6), 938.

Darrow, C. W. (1927). Sensory, secretory, and electrical changes in the skin following bodily excitation. *Journal of experimental psychology*, *10*(3), 197.

Dawson, M. E., Schell, A. M., & Filion, D. L. (2017). The electrodermal system. In J. T. Cacioppo, L. G. Tassinary, & G. G. Berntson (Eds.), Handbook of psychophysiology (pp. 217–243). Cambridge University Press.

E4 wristband user’s manual. (2020, Oct 20). Empatica.

E4 wristband fact sheet. (2020, Dec 14). Empatica.

Emotional Intelligence Institute. (n.d.). Emotional Intelligence Institute Website. Retrieved August 06, 2022, from https://www.emotionalintelligenceinstitute.org/

Fishel, S. R., Muth, E. R., & Hoover, A. W. (2007). Establishing appropriate physiological baseline procedures for real-time physiological measurement. *Journal of Cognitive Engineering and Decision Making*, *1*(3), 286-308.

Glass, J., & Sue, V. (2008). Student preferences, satisfaction, and perceived learning in an online mathematics class. *MERLOT Journal of Online Learning and Teaching*, *4*(3), 325-338.

Greenwood-Ericksen, A., Kennedy, R. C., & Stafford, S. (2014). Entertainment Applications of Virtual Environments. In K. S. Hale & K. M. Stanney (Eds.). (2014). *Handbook of virtual environments: Design, Implementation, and Applications* (2nd ed., pp. 873-880). CRC Press.

Griskevicius, V., Shiota, M. N., & Neufeld, S. L. (2010). Influence of different positive emotions on persuasion processing: a functional evolutionary approach. *Emotion*, *10*(2), 190.

Hale, K. S., Stanney, K. M., Schmorrow, D. & Sciarini, L. W. (2014). Augmented Cognition for Virtual Environment Evaluation. In K. S. Hale & K. M. Stanney (Eds.). (2014). *Handbook of virtual environments: Design, Implementation, and Applications* (2nd ed., pp. 873-880). CRC Press.

Hardy, M., Wiebe, E. N., Grafsgaard, J. F., Boyer, K. E., & Lester, J. C. (2013, September). Physiological responses to events during training: Use of skin conductance to inform future adaptive learning systems. In *Proceedings of the Human Factors and Ergonomics Society annual meeting* (Vol. 57, No. 1, pp. 2101-2105). Sage CA: Los Angeles, CA: SAGE Publications.

Hicks, J. R., & Stewart, W. P. (2020). Learning from wildlife-inspired awe. *The Journal of Environmental Education*, *51*(1), 44-54.

Hu-Au, E., & Lee, J. J. (2017). Virtual reality in education: a tool for learning in the experience age. *International Journal of Innovation in Education*, 4(4), 215-226.

International Society for Presence Research. (2000). The Concept of Presence: Explication Statement. Retrieved 25June2022 from https://smcsites.com/ispr/.

Keltner, D., & Haidt, J. (2003). Approaching awe, a moral, spiritual, and aesthetic emotion. *Cognition and emotion*, *17*(2), 297-314.

King, R. B., McInerney, D. M., Ganotice Jr, F. A., & Villarosa, J. B. (2015). Positive affect catalyzes academic engagement: Cross-sectional, longitudinal, and experimental evidence. *Learning and individual differences*, *39*, 64-72.

López-Carral, H., Blancas-Muñoz, M., Mura, A., Omedas, P., España-Cumellas, À., Martínez-Bueno, E., ... & Verschure, P. F. (2022). A Virtual Reality System for the Simulation of Neurodiversity. *In Proceedings of Sixth International Congress on Information and Communication Technology* (pp. 523-531). Springer, Singapore.

Maier, M., Elsner, D., Marouane, C., Zehnle, M., & Fuchs, C. (2019, May). DeepFlow: Detecting Optimal User Experience From Physiological Data Using Deep Neural Networks. In *AAMAS* (pp. 2108-2110).

Makowski, D. (2020). *Analyze Electrodermal Activity (EDA)*. NeuroKit2. Retrieved August 14 2022 from https://rpanderson-neurokit2.readthedocs.io/en/latest/examples/eda.html

McCorry L. K. (2007). Physiology of the autonomic nervous system. *American journal of pharmaceutical education*, *71*(4), 78. https://doi.org/10.5688/aj710478

McQuiggan, S., Lee, S., & Lester, J. (2006). Predicting user physiological response for interactive environments: An inductive approach. In *Proceedings of the AAAI Conference on Artificial Intelligence and Interactive Digital Entertainment* (Vol. 2, No. 1, pp. 60-65).

National Aeronautics and Space Administration. (1969). *Apollo 11 Lunar Landing Mission Press Kit Part 2*. https://historydms.hq.nasa.gov/sites/default/files/DMS/e000013877.pdf

National Geographic. (n.d.). *Great Pacific Garbage Patch*. https://education.nationalgeographic.org/resource/great-pacific-garbage-patch

Price, C. A., Greenslit, J. N., Applebaum, L., Harris, N., Segovia, G., Quinn, K. A., & Krogh-Jespersen, S. (2021). Awe & Memories of Learning in Science and Art Museums. *Visitor Studies*, *24*(2), 137-165.

Rudd, M., Vohs, K. D., & Aaker, J. (2012). Awe expands people’s perception of time, alters decision making, and enhances well-being. *Psychological science*, *23*(10), 1130-1136.

Rudd, M., Hildebrand, C., & Vohs, K. D. (2018). Inspired to create: Awe enhances openness to learning and the desire for experiential creation. *Journal of Marketing Research*, *55*(5), 766-781.

Sagl, G., Resch, B., Petutschnig, A., Kyriakou, K., Liedlgruber, M., & Wilhelm, F. H. (2019). Wearables and the quantified self: Systematic benchmarking of physiological sensors. *Sensors*, *19*(20), 4448.

Sampson, M. (2022, Jun 08). *The Air Force wants airmen to train without getting their hands dirty*. Task & Purpose. https://taskandpurpose.com/military-tech/air-force-virtual-reality-training/.

Shaffer, F., McCraty, R., & Zerr, C. L. (2014). A healthy heart is not a metronome: an integrative review of the heart's anatomy and heart rate variability. *Frontiers in psychology*, *5*, 1040.

Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. *Frontiers in public health*, 258.

Shan, H., & Mason, P. (2016). A Neuroscience Framework for Psychophysiology. In J. Cacioppo, L. Tassinary, & G. Berntson (Eds.), *Handbook of Psychophysiology* (Cambridge Handbooks in Psychology, pp. 16-25). Cambridge: Cambridge University Press. doi:10.1017/9781107415782.002

Shiota, M. N., Keltner, D., & Mossman, A. (2007). The nature of awe: Elicitors, appraisals, and effects on self-concept. *Cognition and emotion*, 21(5), 944-963.

Shiota, M. N., Neufeld, S. L., Yeung, W. H., Moser, S. E., & Perea, E. F. (2011). Feeling good: autonomic nervous system responding in five positive emotions. *Emotion*, *11*(6), 1368.

Shiota, M. N., Campos, B., Oveis, C., Hertenstein, M. J., Simon-Thomas, E., & Keltner, D. (2017). Beyond happiness: Building a science of discrete positive emotions. *American Psychologist*, *72*(7), 617.

Soliman, M., Pesyridis, A., Dalaymani-Zad, D., Gronfula, M., & Kourmpetis, M. (2021). The application of virtual reality in engineering education. *Applied Sciences*, *11*(6), 2879. https://doi.org/10.3390/app11062879

Valdesolo, P., Shtulman, A., & Baron, A. S. (2017). Science is awe-some: The emotional antecedents of science learning. *Emotion Review*, *9*(3), 215-221.

van Limpt-Broers, H., Louwerse, M. M., & Postma, M. (2020). Awe yields learning: A virtual reality study. In *CogSci*.

Vohs, K. D., & Schmeichel, B. J. (2003). Self-regulation and extended now: Controlling the self alters the subjective experience of time. *Journal of personality and social psychology*, *85*(2), 217.

Wikman, A. (2006). Reliability, validity and true values in surveys. *Social Indicators Research*, *78*(1), 85-110. https://doi.org/10.1007/s11205-005-5372-3

Winn, W. (1993). A conceptual basis for educational applications of virtual reality. Technical Publication R-93-9, Human Interface Technology Laboratory of the Washington Technology Center, Seattle: University of Washington.

Wu, B., Yu, X., & Gu, X. (2020). Effectiveness of immersive virtual reality using head-mounted displays on learning performance: A meta-analysis. *British Journal of Educational Technology*, *51*(6), 1991-2005. https://doi.org/10.1111/bjet.13023

Yaden, D. B., Iwry, J., Slack, K. J., Eichstaedt, J. C., Zhao, Y., Vaillant, G. E., & Newberg, A. B. (2016). The overview effect: Awe and self-transcendent experience in space flight. *Psychology of Consciousness: Theory, Research, and Practice*, *3*(1), 1.

Yates, H., Chamberlain, B., Norman, G., & Hsu, W. H. (2017, September). Arousal detection for biometric data in built environments using machine learning. In *IJCAI 2017 Workshop on Artificial Intelligence in Affective Computing* (pp. 58-72). PMLR.