Virtual Reality and Its Potential for Evaluating Warning Compliance

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Abstract

Behavioral compliance is usually considered the best measure of warning effectiveness. Researching behavioral effects is difficult to carry out, however, due to concerns for safety, ethics, and high costs. Researchers cannot expose participants to real hazards while conducting a research. A realistic scenario that appears risky but that actually has no risk is expensive to conduct in terms of money, time, and effort. This article reflects on the potential of Virtual Reality (VR) as a technique to investigate warning effectiveness, particularly behavioral compliance. VR may help to overcome several key constraints that have limited warning compliance research, such as hazards actually being manipulated. This article focuses on two information-processing stages that will most likely benefit from VR: attention and behavior. Increasingly realistic VR can provide high-quality Virtual Environments (VEs) for use in warnings research. VEs can provide ecological validity and experimental control while limiting actual physical harm. Advantages and limitations are reviewed. © 2010 Wiley Periodicals, Inc.

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1. INTRODUCTION

Warnings play an important role as one of several methods of hazard control to prevent injury and damage. If well designed, they can potentially alert people to latent hazards in the environment. Despite their importance, warnings are not free of problems and limitations. The relatively high potential for failure is the reason why they are considered only a third-line strategy in controlling hazards. Elimination by design and guarding are more reliable methods of hazard control.

There are many kinds of warnings. Most are visual and auditory, but could also be available to the other senses. Warnings could be presented in different ways, such as a safety message in an operator's manual or via video on the World Wide Web. We focus on environmental warnings, mainly signage, in part because new technology can most readily simulate contexts involving environmental warnings.

Warnings' importance as an area has received greater awareness in multidisciplinary scientific communities, as well as governmental agencies and civil society in general. This importance has been reflected in an increase of research, especially from the 1980s and 1990s (Smith-Jackson & Wogalter, 2006), which still continues today. Despite this increase, relatively few studies have measured behavioral compliance. Of these, most have been conducted in laboratory settings; few have been conducted in the field (Kalsher & Williams, 2006; Silver & Braun, 1999; Wogalter & Dingus, 1999). The present article discusses some of the main reasons why research has shied away from using behavioral methods. Background is presented in the context of a theoretical model of mental processing.

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Later, the article focuses on the potential of Virtual Reality (VR) for warning research and presents some work that has already been done. The topic starts with a general introduction about VR and the minimum requirements for its use in research, including the equipment. The ways that VR can potentially overcome the constraints posed in using conventional methods are described. VR drawbacks are also addressed with respect to some of the ways it may be limited, as a research paradigm, by the current state of the art. Issues are identified that may be subject to further research.

2. CONVENTIONAL METHODOLOGIES IN WARNING RESEARCH

This section reviews some of the research methodologies most used to investigate warning effectiveness. The goal is to focus on the major methodological problems that have constrained warning research in past decades, and then follow that up with a promotion of VR as a promising way to overcome the feasibility limitations in behavioral compliance research.

Several models have been proposed to help the understanding of which factors contribute to warning effectiveness (e.g., Lehto & Miller, 1986; Rogers, Lamson & Rousseau, 2000; Wogalter, 2006). Common to most processing models are attention and behavior. We discuss them in detail because these two stages are most likely to benefit with VR research.

Important advantages and disadvantages of field and laboratory warning compliance research are identified and discussed (cf. Anderson & Bushman, 1997; Anderson, Lindsay, & Bushman, 1999; Kvavilashvili and Ellis, 2004). The review of methodologies provides a context for understanding the merits of VR in potentially evaluating warning-related phenomena. VR bridges the gap to overcome some of the limitations of current methods.

2.1. The Communication-Human Information Processing Method

One of the models that has been used extensively to organize research and serve as a cognitive framework is the Communication-Human Information Processing (C-HIP) model. C-HIP breaks down warnings processing into several stages. There are two global parts in the model. The first part involves stages taken from the communication theory (Lasswell, 1948; Shannon & Weaver, 1949), namely source, channel, and receiver. The second part of the model focuses on the receiver and how an individual processes the information. The receiver section is subdivided in substages as attention switching/maintenance, memory/comprehension, attitudes/beliefs, motivation, and behavior. These stages are also connected through feedback loops that show that there can be interactions between stages up and down the model. Contextual aspects, such as the external environment, can aid or hinder warning processing. A bottleneck at any stage could prevent the processing in subsequent stages. DeJoy (1989) presents a literature review that indicates that the likelihood of successful processing of each stage diminishes from the stages of noticing to reading and to complying.

2.1.1. Attention (Switching and Maintenance)

With respect to the receiver, warnings need to be detected by sensory receptors and held long enough to be encoded and understood. Attention is an important research issue because, if a warning is not detected and observed, relevant information processing about them might not occur at all.

The attention switch stage concerns the grabbing and consequent shifting of attention to the warning. In general, stimuli that are conspicuous and prominent are more likely to cause a switch or a shift of attention to it versus other competitor stimuli. The research questions associated with this stage of processing often concern whether users notice the warnings and whether they take any time to examine them. High effectiveness at this stage would be a warning able to attract a person's attention that, otherwise, might be focused on other aspects in the environment and task demands (Wogalter & Usher, 1999).

Attention maintenance refers to the process of holding attention onto the warning long enough so that users can read it or examine it if it is a graphic. The main question at this stage is whether people, after noticing the warning, will spend enough time examining it to acquire information from it. Time will depend on such factors as legibility, density, and complexity of the warning's content. Examples include faded or abraded labels or warnings written too small or in a different language. To successfully hold attention, the warning should have qualities that generate interest so that the person is willing to maintain attention long enough to adequately encode the information from it instead of going on to something else. The effort necessary to acquire information from a warning should be minimized as much as possible.

2.1.2. Compliance Behavior

The last stage(s) of the warning processing sequence in C-HIP and other models is behavior, whether people complied. Warnings should persuade people to take appropriate actions that help to protect them from harm. Examples of common successes of warning compliance are people putting on proper personal protective equipment and avoiding actions that could lead to health-related problems or injury as a consequence of receiving information from a warning. Motivation is the immediate precursor stage of the C-HIP, which can be understood as a force that feeds and energizes the actual doing (or not doing) of behavior. Motivation and behavior are separable because one can be properly motivated to carry out compliance but cannot because of physical limitations (e.g., in a fire emergency, using the stairs by wheelchair users). In some circumstances, compliance can be predicted, with some accuracy, from the outcomes of precursor stages (Kim & Hunter, 1993).

Behavioral compliance is the primary measure of warning effectiveness (Kalsher & Williams, 2006; Silver & Braun, 1999; Wogalter et al., 1987). Compliance can be assessed in laboratory or field settings but involves, almost always, observation of what persons are doing. To promote nonbiased behavior from participants, these studies frequently adopt the incidental exposure experimental paradigm (e.g., Dingus, Wreggit, & Hathaway, 1993; Duffy, Kalsher, & Wogalter, 1995; Hatem & Lehto, 1995; Kalsher, Gallo, Williams, and Wogalter, 2000; Wogalter, et al., 1987), in which participants are not pre-informed that the study concerns warnings. For example, the warnings are presented within a set of tasks that participants are asked to accomplish. Another option for behavioral compliance measurement is to measure it indirectly, through cues or physical traces of behavioral compliance, such as checking later whether protective gloves had been used by indications of being stretched (Wogalter & Dingus, 1999). Epidemiological analysis (e.g., accidents databases) might also be used to measure indications of compliance.

Measuring compliance is difficult due to the costs of effort, time, safety, and ethical considerations; therefore, there has been a noticeable tendency for researchers to take an easier route by measuring a proxy for behavior, namely, reported motivation to behave through self-reported intentions to comply. Intentions to comply are what people report that they would do in response to a warning. Although they are linked to some extent with actual behavior, provide useful information, and offer insight on the processing involved, they are not the same and do not assure that effects can be translated into compliance behavior. Some of the most important factors that have been implicated as influencing compliance (including intentions to comply) are 1) the presence/absence of a warning, 2) warning design features, 3) personal characteristics (e.g., familiarity with situation and/or product and hazard perception), 4) situational factors (e.g., perceived affordances, cost of compliance, social influence), and 5) interactions among these factors.

2.2. Laboratory-Based versus Field-Based Research

Most warning studies can be classified as either laboratory or field research. Each has advantages and disadvantages.

There are numerous advantages of laboratory studies. They usually involve substantial experimental control of variables, have great sensitivity to changes in manipulated conditions, and have high internal validity. Laboratory studies, however, are also often attributed as having reduced external validity compared to field studies. Field studies generally are a better match to the real world, but they also reflect the complexities of the real world with less complete control of variables, with a consequent reduction in internal validity. Most laboratory studies use samples of university students who may not be representative of the intended population; however, laboratory studies have been utilizing increasingly diverse samples. Still, the laboratory approach has clear advantages in that tight control of variables allows for more definitive findings regarding causation to be made. Detailed descriptions of conditions in research articles allow replications of the procedures by other researchers. Laboratory methodologies, however, sometimes study behavior that people may not otherwise engage in their lives. This may lack ecological validity and, thus, such behaviors may not generalize real-world settings (Kingstone, Smilek, & Eastwood, 2008). Nevertheless, most warning research is conducted in the laboratory, and its use has had important practical implications and research contributions in the warnings area. Proportionately few laboratory studies on warnings measure actual behavioral compliance. Instead, most laboratory-conducted research focuses on aspects associated with the attention, comprehension, attitudes/beliefs, and motivation information-processing stages, rather than measure actual behavior.

Laboratory research is conducted because, from the researcher's point of view, field research (such as observing hazardous events to study them) is difficult to conduct due to the rarity and unpredictability of the occurrence of injuries. Clearly, there are high costs associated for all involved. An immense amount of time, work, and money would be necessary, but, more important, there is risk to participants and ethical issues in manipulating real dangers. These limitations are important determinants of what research can be conducted. Consider, for example, how difficult it is for a researcher to study people's use of products in the privacy of their own homes. There are complex sets of limitations in conducting realistic, ecological, valid research. Thus, researchers need to design studies in creative ways to explore warning effectiveness issues.

The current status makes behavioral compliance research on warnings difficult to conduct, and, because of the cluster of difficulties, most of it has been conducted in laboratory environments. Whereas the laboratory is a reasonable option in many cases, it is not free of limitations. For example, a major challenge for warning researchers is to develop a realistic and believable risk situation while at the same time ensuring the participants' safety. To get around this issue, researchers have used simulated risk situations in which no real risk exists or have used situations in which actual risks are present but participants are stopped before there is any contact with a hazard (Wogalter & Dingus, 1999). The creation of such believable risk-appearing scenarios is another difficulty because people will likely not believe that researchers will place them in situations that could actually lead to harm.

Generally it is desirable to use realistic situations to reflect what could occur in an actual real-world situation; however, many of the scenarios used in warning research are simplified, reducing the potential generalizability to real-world situations. An example is one that occurs in the evaluation of symbol comprehension. Contextual information given with symbols during the comprehension test can influence the results in ways that may benefit or limit generalizability. The context may give cues (or clues) that might or might not occur in certain other real-world situations, and this could benefit or limit comprehension performance.

Thus, both laboratory and field paradigms have advantages and disadvantages. Kingstone and colleagues (2008) advocate the use of the joint approach with both laboratory and field studies being conducted in programmatic research. They suggest that researchers start by studying real-world phenomena in the field, and then later moving to the laboratory. Of course, the joint approach could go in the other direction too. The findings from each method could complement the other in a way that the weaknesses of one approach are compensated somewhat by the strengths of the other.

3. VR AS A PROMISING OPTION

The swift development of computers and various technological systems has resulted in a dramatic change in the way we see and use technology. As computer technology has advanced, sophisticated simulations have also become available. With mass production, faster computation speeds, and reduced prices, the equipment necessary to conduct VR has become more obtainable by researchers. Better graphics software and hardware have allowed VR to reach the point of becoming a viable alternative to conventional research paradigms. Use of VR may be able to circumvent part of the already-mentioned limitations of conventional field and laboratory paradigms. It also has the potential to overcome some of the disadvantages of laboratory research by bringing to the laboratory greater realism to better reflect real-world situations and by providing a means to facilitate replication of a context or scenario to iteratively explore complex interactions (cf. Blascovich et al., 2002).

Before VR's potential for warnings research is described, some background on conventional warning assessment methods is presented. In the following sections, definitions and basic concepts essential for understanding the field of VR are presented. The most used VR interfaces are reviewed together with their main advantages and disadvantages. Prior warning research involving VR is described before finally elaborating on the idea that VR has become a real option for use in warnings investigations.

3.1. VR and Virtual Environments

VR is a broad area that has different definitions in the literature. VR consists of a sophisticated interface between people and computers (Hancock, 1995) used to generate Virtual Environments (VEs) to be experienced by the participants. Some authors have chosen to emphasize the technological components, whereas others have given prominence to human experience. According to Steed (1993), the most popular definition points to the idea that VR is a computer-based system containing several key components, such as head-mounted displays (HMD), tracking systems, input devices (in the hand, operating as a locating and grabbing device), audio output, and database. The second category of definitions includes the importance of technological components and also highlights the human experience. To enable a synthetic experience (generated by the VR system), participants are placed into a virtual world or VE. The VE contains synthetic sensory information able to lead individuals to perceive an environmental context, and, if done well, perceive it as if it were not synthetic.

Current VR systems usually have some or all of the following components: a stereoscopic HMD, with a wide field of view; a tracking system to capture hands, head, and body motion; a data glove to capture hand gestures for basic manipulation and exploration tasks; and VR software for rendering the scenario, which also communicates with several external devices and enables automatic data collection. Some studies may benefit from the inclusion of eye-tracking equipment as an optional complementary device to register dwell time and eye gaze.

There are some variants of VR whose classification, accordingly to Gutiérrez, Vexo, and Thalmann (2008), depend on the correspondence between virtual imagery and the real-world scene being displayed to the participants. Gutiérrez and colleagues propose three main categories: VR (in which only virtual images are used); Augmented Reality (AR), in which computer graphics or virtual images are superimposed over real-world images; and Augmented Virtuality (AV), in which imaged portions of the real world are integrated within the virtual world. Both AR and AV combine elements of the virtual and real worlds and are designated as *mixed realities.* Mixed reality systems, as well as teleoperation systems, are not considered VR in a strict sense (Burdea & Coiffet, 2003) and are not covered in this article. Several researchers have used AR to study warnings (e.g. Dzwiarek, Luczak, Najmiec, Rzymkowski, & Strawinski, 2007, Yeh & Wickens, 2001) or to develop innovative technologies to improve person–machine communication in the scope of Augmented Cognition studies (e.g., Holejko et al., 2006; St. John, Kobus, Morrison, & Schmorrow, 2004). Readers are referred to the AR and AV literature for trends in VR-related areas.

VR caught the attention of the public and researchers during the 1990s and was initially considered an exotic field that was difficult to justify, given its expensive costs. Expectations were raised when VR began to be increasingly used in a variety of applications, because people imagined that it would become possible to create imaginary worlds with such high-quality perceived contexts that they would be indistinguishable from the real world. Because technology has not yet allowed high levels of similarity to the real world, these predictions have not yet been achieved. Quality will undoubtedly become increasingly better over time. Even with current levels of quality, VR is becoming useful in a growing number of fields of science, design, training, and entertainment. We predict the same in warning research. Warnings researchers and evaluators should be ready.

A good VR interface simulates a three-dimensional environment with virtual objects and animated entities in which it is possible to interact with different levels of complexity. This can be done with a relatively low monetary cost and in a short time, during which aspects can be manipulated within a highly controlled context as in conventional laboratory research. The goal would be to make highly realistic VR simulation, providing information through several sensory channels, and enabling participants to lose, almost completely, awareness that they are using a computerized interface. Ideally, people will feel immersed in the VE—considering it as real.

The main characteristics of VR are immersion, interactivity, and presence (Bhatt, 2004). Immersion can be defined as the extent to which subjects feel they are cut off from the real world and feel motivated, or caught up, by the VE as if it were real (Ragusa and Bochenek, 2001; Witmer & Singer, 1998). Immersion can be considered sensory/physical or mental (Sherman & Craig, 2003). According to Steuer (1992), immersion is defined by its breadth (e.g., stimulating multiple sensory modalities) and depth (e.g., resolution with respect to vision). The breadth of the immersion will affect the vividness or representational richness. The immersion depth is related to the quality of the available information. For example, a three-dimensional image has more immersion depth than the same image presented in two dimensions.

Interactivity is related to the extent to which subjects have the possibility of real-time changes in the shape and content of VE (Burdea & Coiffet, 2003; Steuer, 1992). Interactivity, due to its captivating power, contributes to the feeling of immersion. Finally, presence is defined as the subjective feeling of being in a place or environment, even when the body is physically in another place (Witmer & Singer, 1998).

Imagination plays an important role in VR, because the individual can decide, despite knowing that one is in a simulation, to perceive and behave exactly as if it were a real-world situation even though the VE contains nonexistent things (Burdea & Coiffet, 2003). Imagination is even more critical when the VEs are fantasies. The feeling of presence is not, however, entirely tied to VE realism levels or immersion. It is mostly tied to simulation content. An elevated feeling of presence can produce intense emotional reactions, such as happiness, anxiety, or sadness.

3.2. VR System

In this section, several aspects and considerations associated with VR systems for warning research are discussed.

A basic VR system involves real-time graphics; stereoscopic display; sound; tracking systems to capture hands, head, and body movements; and interaction devices. Other VR equipment, such as haptic feedback devices (force and tactile), or relating to other senses, can be coupled to increase simulation quality and richness. VR systems can be classified based on the number of participants that can share the same VR experience: individual or group. They also can be classified regarding the VR's immersion quality: fully, semi-, or non-immersive (Gutiérrez et al., 2008).

3.2.1. Display

A general recommendation is to select displays that allow good horizontal and vertical fields of view. To allow the testing of a warning's ability to switch attention, a display capable of peripheral vision is essential. In studies in which the attention stage is less important, it might be acceptable to use a smaller field of view, such as that achieved with computer screens. With respect to immersion and sense of presence, high-resolution visual displays are necessary to vividly simulate the real world.

3.2.2. Sound

Sound is an important part of the real-world experience and contains a richness of information. The combination of sensory modalities increases the sense of presence (Västfjäll, Larsson, & Kleiner, 2002). Sound may not only have important complementary information about the VE, but can also serve as an alternative method of feedback or a new kind of interaction (Kramer, 1995). As a source of information, sound contains small echoes and reverberations that are cues to, for example, distance and direction of the sound source or even space geometry. The presence of sounds may allow a participant to build a mental model of the VE. For example, auditory cues can provide information about nonvisible areas of the VE and about what may take place in those areas. It can also contain details about materials (e.g., walking on stone or carpet, which produce different sounds). Sound is important in situations involving emergency drills or in high-risk situations. These cues include sounds of explosions, the crackle of fire, breaking glass, objects falling on the floor, people running and screaming, sirens and alarms, and so forth. Sound is useful as feedback to confirm that a given action was executed. Examples include the sound of a button being pressed or a machine being turned off. Sound is often part of multimodal warnings.

3.2.3. Interaction Devices

Devices for interaction allow users to navigate, manipulate, and explore the components of a VE. Navigate means to browse the VE; handle means to grasp and/or move objects; and explore means to feel textures, shapes, weight, and other objects' features. The purpose of such devices is to allow individuals to interact with virtual objects and the VE in a way that is the most similar to the real world.

Most navigation modes in VR are characterized as seeming like the world is moving instead of the individual. There is usually an absence of real walking movements. Most VR is without real inherent energy consumption or proprioceptive and vestibular feedback that would be involved in many real-world tasks. Kinesthetic information, transmitted while walking, would increase spatial orientation in the VE (e.g., Bakker, Werkhoven, & Passenier, 1998; Chance, Gaunet, Beall, & Loomis, 1998) and raise the feeling of presence and immersion (e.g., Slater, Usoh, & Steed, 1995; Usoh et al., 1999).

Manipulation of virtual objects is potentially important in some compliance research. Capture of hand and finger movement using data gloves can be used in basic tasks that involve pointing or touching something inside the VE. Thus a data glove with an associated tracker might be sufficient for most studies. In manipulating objects, however, haptic feedback will greatly increase the experience quality in VR. Haptic feedback may include force, tactile, and proprioceptive data. There are, however, some drawbacks regarding intrusiveness, complexity, and cumbersomeness of the devices used to give such feedback that may restrain natural movements. Also, the majority of such systems were designed for a seated posture. Because feedback is usually transmitted by vision or audition, increasing the quality of such feedback might diminish some of the need to have high-quality haptic feedback.

3.2.4. Motion Capture Devices

Real-time motion capture is important to enable interaction because it involves gathering data about the participant's position, body segment orientation, posture, and gestures. This is achieved by the direct evaluation and recording of the real person's actions, for immediate or later analysis, and playback. Realistic manipulation of virtual objects is difficult and complex because it requires capturing a real user's motion, transposing the motion to the VE, defining the behavior that the virtual object will exhibit, and then giving a real-time feedback to the user, all of which require fast processing speeds.

3.2.5. Software

Software is one of the most important parts of VR systems. Its most important task is importing and rendering the geometry of the VE, together with other specified detailed elements and textures, such as lights and shadows. In research, automatic data collection and summarization is useful. Data collected could involve measurement of many different kinds of aspects, such as the occurrence of sudden movements, individuals' looking behavior, amount of time interacting with selected elements, and so forth.

4. WARNINGS RESEARCH USING VR

4.1. Previous Work

Some studies have already used VR as a research tool in environmental warnings research. These studies are discussed next. The focus of this article is on visual environmental warnings, but readers are asked to see existing research involving VR and auditory warnings in other sources (e.g., Lin et al., 2009).

Several studies have used VR to simulate emergency evacuations during fire situations. In one study, Glover and Wogalter (1997) sought to determine if VR was an adequate technique for studying behavioral compliance during an egress task. They used a computerized simulation of an underground mine. Three variables were manipulated (time stress, salience, and sign type). Results indicated that signs with salient features increased compliance compared to signs without those features. The time stress and sign type failed to show significant effects. Louka and Balducelli (2001) described the VR potentialities for training rescue teams to face fires in tunnels. They had many aspects of the environment built into the simulation, including tunnel structure, safety equipment, ventilation/air extraction systems, flames and smoke propagation, as well as people and vehicles. Ren, Chen, Luo (2008) have used VR to simulate a fire in an underground subway station. The VR application allowed the simulation to be repeated as many times as needed. The realistically modeled VE allowed participants to navigate an environment filled with smoke and flames while, at the same time, virtual humans ran to escape in several directions. Gamberini, Cottone, Spagnolli, Varotto, and Mantovani (2003) used a VE to assess how participants responded to a fire emergency in a public library. They compared the participants' behavior in an explorative navigation task with a hurried escape after an unexpected outbreak of fire. Fire intensity and participants' distance from the exit at the outbreak of fire were varied to create different degrees of danger and different degrees of difficulty in the task of leaving the premises. The time required to leave the building was recorded as well as how frequently the virtual body bumped against virtual objects. Results showed that 1) the appearance of the fire emergency triggered important changes in the way people moved in the VE and 2) such changes were all adaptive responses to an emergency situation. People seemed to recognize a dangerous situation in a VE and readily produced adaptive responses, suggesting VE as suitable for emergency simulations and for use as an effective training tool. Shih, Lin, and Yang (2000) compared evacuation times using VR with one calculated by traditional mathematical methods. Data regarding routes, traveled distances, and behavior from each participant were collected. Exit signs were manipulated. Participants frequently chose routes that were different than those indicated by signs, particularly when there was a shorter alternative egress route available. Most occupants intended to evacuate from the direction they entered regardless of the signs and the smoke. The smoke in the VE negatively affected the route selection as well as the signs' effectiveness to help participants find an exit. Tang, Wu, and Lin (2009) used VR to determine whether different emergency signs facilitated egress. They found that signs assisted in wayfinding. When faced with both an emergency direction sign and an exit door, however, almost half of the persons choose to take the door instead of following the directions posted on the sign. At the first intersection participants did not pay much attention to signs indicating the exit direction. Later, at the second and third intersections, the percentage of persons attending to the signs increased.

As mentioned earlier, conception and development of VR simulations can be complex, time consuming, and expensive. Smith and Trenholme (2009) suggested that video game technology might be a less expensive way to generate such simulations. Their study used a building evacuation fire drill to investigate the usability and realism of the constructed VE and to determine whether the computer game development tools were suitable for rapid prototyping VEs. Various metrics were collected, such as building evacuation times, subjective responses using questionnaires, and audio and video data. Participants were also asked to describe their experiences out loud. The results showed that VR experience varied depending on previous experiences with computer games. Evacuation times were negatively correlated with participants' video gaming experience, with more experienced participants completing the scenarios in less time.

The majority of the previously described fire evacuation studies were aimed at predicting evacuee behavior or criticizing buildings' layout. Only a few studies have been done with the purpose of evaluating warnings' impact on peoples' behavior. Most have not used immersive VR, except the research described earlier by Gamberini and colleagues (2003).

Previous VR research examining warning effectiveness has not employed any object manipulation tasks, probably because of difficulties in incorporating tactile and haptic stimulus feedback into current VR systems. The main task in most previous research consists of asking the participants to make a route selection. The lack of usable object manipulation is a severe limitation because most warnings concern behaviors or tasks that involve physical manipulation of objects, controls, and so forth.

4.2. VR in the Study of Attention and Behavior Processing Stages

In this section the major potential advantages and limitations of VR in studying warnings effectiveness are discussed. Particular focus is on the attention and behavior stages of warning processing of the C-HIP model, because it is those two stages that will be revealed most by VR study.

4.2.1. VR Research on the Attention Stage

Time to respond to presented stimuli will provide information about a warning's attention-getting aspects. More salient warnings will be looked at sooner and responded to sooner than will be less salient warnings. Head and eye tracking can collect measures of attention switch (as in looking behavior) and maintenance dwell time.

Using self-reports is an indirect way to assess attention and is a method available to study attention without VR. VR can be used, however, to facilitate the acquisition of subjective data associated with attention. For example, after a virtual walkthrough, participants can be questioned about what they had seen, where they were looking, and why, among other issues. Of course, caution is necessary in considering self-reports due to various biases and memory lapses.

An advantage of VR in the attention stage is the manipulation and study of potentially influential factors, such as examination of stimuli that are presented for a short duration, in small size, in contexts of low light and contrast, and in the presence of fog, smoke, and so forth. The entire interaction, including what participants' saw (their looking behavior or viewpoint) during the VR experience and physical (body) behavior exhibited during the interaction, can be recorded. A downside of current VE experience is the poor quality of the displayed visual world (resolution, responsiveness, realism, detail, and refresh time). These issues are factors in disorientation, simulator sickness, eyestrain, and visual aftereffects.

4.2.2. VR Research on the Behavioral Compliance Stage

Behavioral compliance is the culmination of several processing stages in the C-HIP model. Warnings should persuade people to take actions to protect them from harm, such as donning appropriate personal protective equipment and avoiding actions that could lead to health-related problems or injury. Simulation of realistic hazardous contexts by VR can potentially provide greater ecological validity than can most other methods, except, of course, actual compliance in the real world. The simulation of real-world events in which participants can enact warning compliance is one of the main contributions of VR to this area of research. With VR, researchers can create fictitious situations that appear hazardous but in which safety is assured. Compliance can be assessed globally, such as at the end of the complete set of interactions, or partially, such as by collecting "points" accrued for carrying out parts of the behavior or conversely registering "penalty points" for skipping certain behaviors within a critical time period.

Factors, such as cost of compliance (e.g., Dingus et al., 1993; Wogalter, Allison, & McKenna, 1989) or social influence (e.g., Chy-Dejoras, 1992; Edworthy & Dale, 2000; Racicot & Wogalter, 1992; Wogalter et al., 1989), can be manipulated within a VR simulation. With cost of compliance, for example, adding inconvenience to the task to be executed may lead to safety behaviors not being carried out. Regarding social influence, it is possible to include, inside of the VE, virtual humans who exhibit predefined compliant versus noncompliant behaviors (Blascovich et al., 2002). Previous cost of compliance research demonstrates that, when target users see others complying with the warning, then they are more likely to comply. The opposite is also true: Seeing others not complying with the warning, they are less likely to comply.

Other physical measures reflecting the behavior stage include perspiration (skin conductance), heart rate, pupillary response, facial electromyographic activity, and nonverbal behavior inferred from posture, facial expressions, and direct eye contact.

One current drawback of using VR to assess the behavioral compliance stage is the extent to which participants feel a sense of presence, or, in other words, how much they feel that they are in a real situation. If participants do not believe that they are immersed, they could be insensitive to the manipulations or yield invalid or nongeneralizable results. Another potential problem is that frequent users of sophisticated computer games might adopt a game-type strategy when in a VE. These participants might exhibit nonrealistic behaviors toward hazards because generally in playing games there are no real injury consequences. Users are playing increasingly more realistic, sophisticated games. Thus, some of the performance in a VE could be an artifact of extensive computer game playing. The game-playing aspect can also affect not taking the situation presented seriously.

Using VR for the testing of warnings also has some other negatives associated with it. There is the risk of simulator sickness, like motion sickness, which can be unpleasant. Also, some of the added realism is compromised by locomotion interfaces, which can affect the reality of the experience. Natural walking is difficult to achieve. Usually people move by "flying" around or using a mobile chair, cart, or platform. Frequently, navigation is achieved through a joystick or another manual controller. Fortunately, haptic/touch interfaces and feedback have dramatically improved in recent years. Finally, researchers need to be sensitive to avoid any psychological effects. Certainly few institutional review boards (IRBs) at research institutions will allow participants to be scared out of their wits. Nevertheless, studying people's behavior in situations perceived as mildly risky (actually safe) should benefit the measurement of warning effectiveness and enable better safety-related decisions.

5. CONCLUSION

The main focus of this article was to explore VR's potential in investigating warning effectiveness factors. VR provides a realistic context, which often benefits external/ecological validity. VR can offer repeatable experimental conditions, benefiting internal validity. High-quality VR can make participants feel as if they are actually in the scenario. Diverse VE situations, such as an emergency room or even a coal mine, are possible as. VR offers considerable potential for warning researchers and designers to evaluate factors influencing the behavioral compliance of warnings.

This article reviewed research concerning attention and behavior stages and discussed issues concerning laboratory and field methods. Advantages and disadvantages of methodologies and how VR can contribute were discussed. Important methodological constraints, such as ethical considerations, have inhibited the growth of behavioral compliance research, which may be overcome by the use of VR.

VR offers the possibility of overcoming important methodological limitations in behavioral compliance research, particularly ethical and safety issues. VR can potentially provide realistic, interactive, quasi-real, and believable situations in which behavior can manifest in all of its variety and amplitude. VR can enable control of manipulated experimental variables in a repeatable way to benefit internal validity. Because behavioral compliance is the most difficult stage to evaluate with conventional methods, VR could make substantial inroads into research on factors influencing compliance. VR could enable additional testing of warnings by product and equipment manufacturers of the warning systems in the context of when they might work and measure responses. The testing could enable measurement of warning quality to see if the warning is working as intended. The ability to measure behavioral compliance through VR could improve safety in data-based ways.

The development of a VR system to support VEs is challenging. Persons running the project need to work with others from diverse areas of expertise. Although development can be costly in terms of time, money, and effort, there is great potential.

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