van Gelder *et al. Crime Science* 2014, **3**:10
http://www.crimesciencejournal.com/content/3/1/10

Crime Science
a SpringerOpen Journal

SYSTEMATIC REVIEW Open Access

Using virtual reality in criminological research

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Abstract

Since the pioneering early studies of the 1990s hinted at its promise as a research method, virtual reality (VR) technology has increasingly been used by social scientists. Given recent developments that have greatly enhanced realism, reduced costs, and increased possibilities for application, VR seems well on its way to become an established research tool in the social sciences. However, as with other methodological innovations, the field of criminology has been slow to catch on. To address this gap, this article explores the potential of VR as a tool for crime research. It provides readers with a brief and non-technical description of VR and its main elements and reviews several applications of VR in social scientific research that are potentially relevant for criminologists. By way of illustration, we identify and discuss in more detail different areas in which we think the field of criminology can particularly benefit from VR and offer suggestions for research. Some of the equipment available on the consumer market is also reviewed. In conjunction, the different sections should equip readers interested in applying VR in their own research with a fundamental understanding of what it entails and how it can be applied.

Keywords: Virtual reality; Virtual environments; Crime; Delinquency; Crime research; Innovative methods

Introduction: what is virtual reality?

Whether we realize it or not, most of us are familiar with and have used virtual environments at some point, and perhaps more often than we realize. Think, for example, of a virtual tour you took, a gaming device such as the Wii, Playstation or Xbox you once (or frequently) played with, online platforms such as World of Warcraft or Second Life you have wandered around in, a 'flight' you took in a simulator in a game arcade, or the time you used the IKEA website to design your new kitchen. These different examples hint at the range, level of complexity, and diversity of what can be captured under the term 'virtual environment'.

The term virtual reality (VR) is generally used to refer to an artificial or computer-generated, three-dimensional representation of reality, which is experienced through the senses and which is interactive, i.e., in which the user's actions (co-)determine the course of the interaction. A virtual environment (VE) is a digital space in which a user's movements are *tracked* and his or her surroundings *rendered*, that is digitally recomposed and displayed back to the user in accordance with those movements (Fox et al. 2009). Think, for example, of a game controller or joystick that tracks the user's motions in the real world and moves the player's character forward on the computer screen, rendering a new environment (Fox et al., 2009). Through a computer-generated image or animated character, an *avatar*, a user can move around the virtual world and pick up and interact with virtual objects in the going (Ticknor & Tillinghast, 2011).[a] *Interactivity* is key in this respect as, much more than is the case with traditional media, in a virtual environment the user has a role within the medium, and his/her actions influences how the experience or scenario unfolds in real-time (Fox et al., 2009).

Another important element of VR is its level of *immersion*. In case of immersive virtual reality (IVR), a user is perceptually surrounded by the virtual environment and his/her awareness of the real world is minimized (Loomis et al. 1999; Ticknor & Tillinghast, 2011). As real world sensory input is blocked, this can generate the impression that one has actually stepped inside the virtual environment and create an illusion of involvement with the artificial world (Witmer & Singer, 1998). Immersive virtual reality is typically achieved by having participants wear a *head-mounted display* (HMD) (see Figure 1). A HMD is a headset or helmet that replaces a desktop monitor in the sense that it contains displays (and possibly earphones) attached to it that provide a wide, stereoscopic view of the computer-generated environment (Fox et al., 2009).

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Figure 1 Virtual reality technology elements: 1) head-mounted display, 2) headphones, 3) controller, 4) (rendering) personal computer.

Special trackers provide the coordinates and rotations of the user's location in the virtual environment, which, in turn, are communicated to the rendering computer, which feeds the appropriate video back to the participant through the HMD. Software and (optionally) specialized hardware can add spatialized sound such that users hear sounds as emanating from the surrounding 3-dimensional auditory space (Loomis et al., 1999:558). *Presence*, finally, refers to a subjective sense of "being there", i.e., in the place depicted by the virtual reality rather than the physical place where the user's body is actually located and the tendency to respond to the virtual events and environment as if they were real (Slater, 2004; Slater et al., 2006). Presence is related to immersion in the sense that a greater level of immersion is also likely to generate a greater sense of presence (Ticknor & Tillinghast, 2011). However, whereas immersion refers to the actual configuration of the interface and VR setup, presence refers to a psychological state that reflects emotional, physical and cognitive engagement with the VE.

Virtual reality in social scientific research

Although VR and VEs became known to a wider audience in the 1990s, the seminal ideas and even prototypes date back more than half a century. Blascovich et al. (2002):105 even go so far as to argue that "social psychologists have been creating virtual (i.e., synthetic) environments, even immersive ones, for decades using hard scenery, props, and real people (i.e., confederates)". Two examples of well-known social psychological experiments that have used such type of (analogue) VE that precede the modern-day computer-generated VEs and that are of particular interest from a criminological perspective, are Stanley Milgram's (1963) obedience experiment and Philip Zimbardo's Stanford Prison Experiment (Haney et al., 1973).

In Milgram's obedience experiment, people were recruited to participate in a memory and learning experiment held in a social research laboratory at Yale University. Participants were instructed by a lab-coated experimenter to give electrical shocks using a scary-looking (bogus) device that was introduced as a 'shock generator' to another participant, in reality a trained research confederate, ostensibly as part of a learning task. The shock generator was equipped with toggle switches labeled with voltage levels that ranged from 15 to 450 volts and verbal designations ranging from 'Slight Shock' to 'Danger: Severe Shock'. An event recorder wired to the shock generated measured the duration and latency of each 'shock' that was administered. The study showed that ordinary citizens were under the belief that the setup and experiment were real and were willing to administer apparently lethal electric shocks to strangers when instructed to do so at the behest of an authority figure.

The other early well-known example of a hard scenery 'virtual environment' is the Stanford Prison Experiment by Zimbardo and colleagues in which a mock prison was set up in the basement of Stanford University. The participating students in this study were randomly assigned to either guard or prisoner roles. Within one week into the experiment, those students that had been assigned the role of prison guard had started to psychologically abuse their 'prisoners'. The latter often passively accepted the abuse and, at the request of the guards, readily harassed other prisoners who attempted to prevent it (Haney et al., 1973). Besides raising serious ethical concerns, both studies show the strong effects artificial environments can have on the behaviour of people.

As mentioned above, in common parlance when talking about VR or virtual environments, what is referred to are environments that are computer-generated instead of made up of hard scenery and tangible real-world props. As will be discussed in more detail later in this article, VEs carry various advantages over 'analogue' environments in terms of cost, flexibility, replication, reusability, experimenter control, and the ease with which adaptations can be made to the environment and, hence, the research design. Provided they are realistic enough, digital VEs can operate as a substitute for the real-world physical environment which makes them a highly relevant and interesting tool for social scientific research.

In the next section, we will provide an overview of several applications of VR in social scientific research. Fox et al. (2009), distinguish between the use of VR as a technology in and of itself, VR as an application, and VR as a method. The first type of study can address questions such as to what extent the human experience within a virtual environment is similar to or different from experiences in the physical world. The second type creates virtual environments with the intention of *application* outside of the laboratory in order to achieve real world goals. For example, surgical virtual environments have been developed to familiarize doctors with new medical procedures and flight simulators provide training environments for pilots (Fox et al., 2009). The third type regards the use of virtual environments as a *method* to study social scientific phenomena, enabling the replication and extension of real world experiments in a more controlled environment and also helping researchers create stimuli that may be too costly or impractical to achieve in the real world. Whereas all three applications are potentially relevant for criminologists, for the present purposes, and in line with the goals of this special issue, of most relevance here is the use of VR as a method.

Relevant studies using VR in the social sciences

Recently, Slater et al. (2006) carried out a variation of Stanley Milgram's 1960s obedience experiment. Recall that Milgram's experiment aimed to understand obedience by demonstrating that people would administer severe and dangerous electric shocks to a stranger when instructed to do so by an authority figure. In their 'virtual reprise', Slater et al. employed a similar paradigm to the one used by Milgram but used an immersive VE instead of hard prop scenario. However, instead of examining obedience in itself, the authors looked at the extent to which participants would respond to such an extreme social situation as if it were real. That is, in the Slater et al. experiment, participants delivered 'electric shocks' to a virtual 'trainee' when she made errors during a word association memory test. The virtual trainee protested against the shocks in similar ways as the confederate in the Milgram study. The variable of interest here is whether participants in this study would experience such high levels of presence that they would display signs of distress or behaviors that indicated that the virtual person was being treated as real. This was the case. Even though participants knew that neither the trainee nor the shocks were real, they tended to respond to the situation at the subjective, behavioural (e.g., withdrawal from the experiment) and physiological (e.g., heart rate, skin conductance) levels as if they were. The authors conclude that their results "reopen the door to direct empirical studies of obedience and related extreme social situations, an area of research that is otherwise not open to experimental study for ethical reasons, through the employment of virtual environments" (Slater et al., 2006).

Indeed, the Slater et al. (2006) study shows that powerful experiments with VR can usefully be carried out when ethical or safety considerations militate against using real-world situations or real humans as participants. One example of such research that comes to mind for the criminological context is (experimental) research on guardianship and bystanders. The well-known bystander effect refers to the finding that the larger the group of people witnessing a violent event, the less likely it is that someone will attempt to intervene or help (Darley & Latané, 1968). As Slater et al. (2006:6) note, to study this in the real-world context, researchers are forced to at best use videos that require people to judge likely responses to such situations even though we know since the original Milgram study that taking people's opinions about their own and others' behaviors in such circumstances at face value is far from reliable.

In a recent study, Slater et al. (2013) examined the bystander effect in a VR setting. Specifically, this study addressed the question whether the occurrence of the bystander effect in the case of violence is contingent on the victim belonging to a participant's in- or out-group. Participants in the study, all supporters of Arsenal Football Club, entered a VE representing a bar in which they were approached by a male virtual human (V, the victim) and talked with him about football. In one condition, V wore an Arsenal football shirt and spoke enthusiastically about the club (in-group condition). In the other condition, V wore an unaffiliated red sports shirt, and asked questions about Arsenal without special enthusiasm, using neutral responses and displaying ambivalence about Arsenal's prospects (out-group condition). After a few minutes of this conversation another male virtual human (P, the perpetrator) who had been sitting by the bar walked over to V and started an argument that he continually escalated until it became a physical attack. The researchers found that participants in the in-group condition made more attempts at physical and verbal intervention than those in the out-group condition. Furthermore, for those in the in-group condition the number of physical interventions was associated with the belief that the victim was looking towards them for help.

In sum, both the Milgram and the Zimbardo experiment illustrate that, on the one hand, VR technology is able to elicit social and physiological responses from participants that resemble responses in the real-world. That is, participants may respond to avatars as if they are human in full knowledge that they are not real. On the other hand, these studies demonstrate that VEs make suitable environments to study social phenomena that are difficult to experimentally examine in the real-world.

Virtual Reality as a replacement of written vignettes?

Within experimental psychology, researchers traditionally face the trade-off between maintaining experimenter control, and hence maximizing internal validity, or achieving high levels of ecological validity (Blascovich et al., 2002; Loomis et al., 1999). This has generally resulted in highly controlled but also contrived situations in sterile university laboratories at the cost of losing ecological validity (Blascovich et al., 2002). VR can, to some extent, do away with the necessity of making this trade-off through its ability to increase the realism of experimental situations. As Loomis et al. (1999) observe, cognitive and affective states are often induced by verbal instructions or written passages, such as scenarios or vignettes[c], the effectiveness of which in terms of variability across participants varies according to attentional, motivational and imaginative capabilities of participants. Vignettes create illusions of reality in which the imagined or implied presence of others often plays a role (Blascovich et al., 2002). By more directly eliciting participants' cognitive and affective processes, VR technology, immersive VR in particular, can substantially augment experimental realism and reduce the variability in the results of these manipulations (Loomis et al., 1999: 559; but see also section Relevant Limitations of VR in this article).

While the field of criminology may be less "experimental" in nature compared to social psychology, the use of written vignettes is a widely used method by criminologists, such as deterrence and rational choice researchers and other researchers interested in criminal decision making. We think that the use of VR and VEs can improve and update this type of research. By way of illustration, consider the following scenario, which has been used repeatedly in criminological research (e.g., Schoepfer & Piquero, 2006; Mazerolle, Piquero & Capowich, 2003):

> "It's Friday night, Mike and Lisa, who have been dating for two years, go into the Dutch Goose for a few beers and dinner. While drinking their beers, Mike excuses himself and goes to the bathroom. While he is away, another guy, Joe, who is with his friends, starts talking to Lisa and sits down at her table. Mike returns just as Joe is asking Lisa for her phone number and asks the guy if he has a problem, because he is coming on to his girlfriend. Joe stands up and tells Mike that Lisa does not have a ring and is therefore allowed to talk to whomever she wants. Mike does not like this very much, so he motions to Lisa for her hand so they can leave. Meanwhile, Joe's friends stare Mike down. Then Joe pushes Mike's hand down. Mike grabs a beer bottle off the table and hits Joe in the head with the bottle".

After reading this scenario, research participants are posed the question: "How likely is it that you would act like Mike?" In other words, in this scenario the participant is challenged to picture himself in a crowded, noisy bar and, at least to some (unspecified) extent, to be under the influence of alcohol. Furthermore, the participant is to imagine having a girlfriend, and to picture her in his mind, and also to imagine a group of people staring him down, and being engaged in a rapidly escalating exchange with 'Joe'. Importantly, participants are asked to imagine performing a behavior, breaking a bottle over someone's head, that they are likely to be highly unfamiliar with.

All this requires developed imaginative capabilities on the part of the participant and substantial cognitive effort if this task is taken seriously. Importantly, research shows that people are fairly limited in their ability to predict their future behavior, which makes it questionable whether self-reported intentions are valid proxies of real-world behavior, especially in situations that are uncommon or situations that regard unconventional behavior (Exum & Bouffard, 2010). As was remarked earlier in the context of the Milgram obedience study, behavioral intentions should not be taken at face value. Additionally, studies using written vignettes generally do not consider the impact of altered and 'hot' states of mind on behavior. Altough extant research shows that people rarely fully appreciate the impact visceral factors and intense emotions have on their behavior when they are in an emotionally neutral state (e.g., Loewenstein, 1996; Ariely & Loewenstein, 2006). In the case of the Dutch Goose scenario, it is likely that participants will underestimate the impact of anger as a result of being insulted will have on their behavior. In a similar vein, the influence of the alcohol consumed on behavior is also hard to predict from a 'cold', i.e., not intoxicated, state. Consequently, participants are unlikely to accurately predict how they would behave in a situation similar to the one described in the scenario. Interestingly, Exum (2002) used a modified version of the above scenario in a study in which both anger levels and alcohol levels were experimentally manipulated. Neither alcohol, nor anger, nor their interaction turned out to be related to participants' intentions to aggress in this study. On the basis of the above, we speculate that it may have been the fact that the scenario was presented to participants in written form, and therefore failed to evoke a vivid mental imagery, that could account for the absence of significant effects.

Can these problems be addressed or overcome through the use of VR? The Slater et al. (2013) study on the bystander effect already hinted at some of the possibilities. For one thing, a research approach using immersive VR could visually depict the bar in which the conflict unfolds, the characters that play a part in it, and the escalation between Joe and Mike, and do so from the perspective of Mike (or that of a bystander). Hence the viewer can be placed square in the middle of the situation by immersing him in the scenario and witness the course of events as if he were an actor in it. Such immersion should make answering the question "How likely is it that you would act like Mike?" more straightforward and reduce the cognitive burden for participants. As the Slater et al. (2006) study showed, virtual humans can elicit psychological responses that resemble those that people experience in the presence of real humans. Hence a VR scenario depicting the conflict unfolding in the *Dutch Goose* is likely to be more ecologically valid compared to a written version of the same scenario. Responses towards a virtual version would therefore be more likely to approach real-world behavior than would be the case for the written vignette, although this, of course, still remains to be empirically tested.

Additionally, the likelihood that a participant would act like Mike is probably also influenced by the physique and nonverbal behavior of Mike (and his friends), features about which the written vignette is silent. An experimental setup using VR would also allow for the systematic variation of the appearance of avatars and environmental features, e.g., lighting, presence of others, type of bar, and assess their specific influence. Furthermore, a VR setup of the Dutch Goose vignette or a similar scenario can be used in combination with physiological measures such as heart rate, blood pressure or galvanic skin response, (see the article by Cornet in this special issue for more information on the application of physiological measures in criminological research). Written vignettes are unlikely to generate physiological responses of similar intensity as VR does. Furthermore, in the case of VR the timing of the physiological response can be linked to specific events occuring in the VE whereas this is impossible in the case of written scenarios.

While, arguably, the same can be achieved using a real-world experimental set-up with real actors as confederates, there are various reasons why VR may be the preferred option. In situations using real actors, there is a loss of experimental control, through confederates or trained actors' verbal and nonverbal behaviour that may cause unintentional variation in the stimulus. The use of VR also allows exact replication (Blascovich et al., 2002) which may be crucial for developing a cumulative body of scientific knowledge (see Townsley & Johnson, 2008). Real-world confederates may vary in terms of appearance and physique, dress, nonverbal cues, etc., all of which can be standardized using VR. Additionally, using VR, an avatar or participants' race, gender, age, weight, etc. can be experimentally changed, holding all other variables constant, which reduces the risk of potentially confounding variables. Furthermore, a VE can be transposed entirely to any location on the globe.

In sum, instead of asking participants *to imagine* themselves to be in a described situation, VR allows the researcher to actually *immerse* participants in that situation. This increases the sensation of being present in the VE and is likely to evoke more genuine and valid responses, especially in the case of novel or stressful situations, or situations describing unethical, unconventional or socially undesirable behavior, which more often than not tends to be the behavior of interest for criminologists. Additionally, VR can be used in combination with any number of other objective and physiological measures, such as the proximity between participants or stimuli in the environment, eye movements, gaze, heart rate, skin response, brain activity, etc.

Related to, but different from the issues described above, which pertain to the mundane realism-experimental control trade-off, ethical issues and the ecological validity of research designs, VR can also serve as a useful tool for theory testing or for the study of phenomena that are hard to study in the real world for practical reasons. In the following section, we will discuss several examples of such research. The first example comes from a recent study by Van Gelder et al. (2013).

Theory testing: meeting your future self

Van Gelder et al. (2013) used VR technology to tackle a long-standing problem in criminology. Delinquent acts have in common not just their illegality, but the fact that they offer immediate benefits, such as cash, sexual gratification or excitement, while simultaneously entailing the risk of long-term costs greatly exceeding the benefits (Hirschi, 2004). Consequently, what sets individuals with a high criminal propensity apart from their non-delinquent counterparts is a tendency to focus on immediate benefits while failing to adequately take into account the long(er) term costs of their behaviour, such as the social and formal sanctions that may follow delinquency (Gottfredson & Hirschi, 1990). However, the cognitive mechanism underlying this failure is not yet fully understood. Van Gelder et al. (2013) hypothesized that delinquent individuals have difficulty imagining themselves in the future. That is, their 'present' and 'future' selves are psychologically unconnected, as a consequence of which they fail to take delayed consequences into account and tend to opt for immediate gratification by way of criminal behaviour. Therefore, the authors reasoned, instilling a greater sense of vividness of the future self should motivate individuals to act in a more future-oriented way and consequently reduce their tendency to make delinquent decisions.

To test this hypothesis, Van Gelder et al. (2013) used immersive VR to have participants meet their future self. Their IVR environment consisted of a room with a virtual mirror hanging in the middle of one of its walls. When participants in the experimental condition approached the mirror, instead of seeing their present selves, they saw a highly realistic version of their future self, that was created using specialized software. After the VR experience, participants took a trivia quiz (see Nagin & Pogarsky, 2003), allegedly as an optional bonus for their participation in the experiment, but in reality the dependent variable and measure for delinquent behaviour, for which they could win cash by performing well. That is, participants were told that answering seven or eight out of eight questions correctly entitled them to the €7,- bonus, which were attached to the test booklet in an envelope. As the correct answers were shown on the last page of the booklet participants had an opportunity to cheat, even though they were explicitly instructed not to look at the answers before finishing the quiz. However, the quiz was rigged to make it almost impossible to win. People claiming seven or eight correct answers could therefore be safely assumed to have cheated. As predicted by the researchers, in comparison to participants in the control group, who had seen an avatar of their present self in the virtual mirror, participants who had seen their future self were significantly less likely to cheat on the quiz.

In sum, the Van Gelder et al. (2013) study demonstrates that vividness of the future self predicts delinquency and can be experimentally manipulated. This study is an illustration of an application of (immersive) VR that allows for testing a phenomenon in a way that would have been difficult to achieve otherwise; to have participants actually 'meet' their future self. Finally, this study showed that the effects of the manipulation, which took place entirely in the VE, carry over into the real-world.

Observing crime in action: virtual burglary

As Van Gelder and Van Daele mention in the editorial introduction to this special issue, one of the main problems that have plagued the field of criminology throughout its history, is that due to the fact that crime tends to be a covert activity, crime in action can rarely be observed, let alone in such a way as to allow for systematic empirical study (Van Gelder & Van Daele, 2014). Even if practically feasible, ethical considerations often militate against such research. Consequently, our knowledge of the actual offending process relies in large part on indirect evidence, which poses obvious limitations to understanding the criminal event. Consider research based on interviews with offenders for example. The reconstructive nature of interviews with offenders about how they executed their crimes, are prone to recollection biases that threaten the validity of research findings. For example, important events (e.g., the presence or absence of bystanders) may have been forgotten, sequences may be reversed in memory, and all information that was processed below the threshold of consciousness cannot be retrieved from memory. Social desirability is another way in which bias may color the results of this type of research.

In certain cases the use of VR may provide, in certain cases, a way to overcome these issues as it allows researchers to study the criminal event as it unfolds. A good example of such research is recent work by Nee and colleagues (in press), who compared ex-burglars and university students on a mock burglary using both a real and a simulated environment to examine how differences in expertise influence how these groups go about breaking into a house. Nee et al. (in press) had a small group of experienced ex-burglars and a small group of students with no prior offending histories undertake mock burglaries in a real house and in a replica of the same house in a simulated environment to observe and compare their behaviour. The study aimed to measure how differences in expertise would influence how novice and expert burglars go about burglarizing houses assuming burglars would not only take fewer items that had higher value, but also that they would navigate the house in a more systematic way. Furthermore, the study also aimed to demonstrate that findings from the burglaries of the real house would be replicated in the virtual house. The results support both the expertise hypothesis and also the hypothesis that there are few differences in the way in which burglars went about burglaring the real house and the simulated house, which supports the idea that simulated houses or structures can be usefully employed to study burglary in action.[d]

Perceptions of risk and victimization: navigating a virtual city

In another recent study, Park and colleagues (Park et al., 2012) developed a semi-immersive VE not to study the offending process, but to examine context-specific assessments of victimization risk. These authors used a VE to examine the impact of high-risk environmental contexts on decision-making with a view to demonstrating the value of this technology for criminological theory and crime prevention (Park et al., 2012:31). Decision-making in this study was assessed across a series of binary, forced-choice, decisions while journeying through a virtual city based on images of inner-city Vancouver, Canada. The VE was projected on a large (4 × 5 meter) projection screen and participants could navigate and interact with it using a game controller. Participants were presented with a summary map that outlined the broad environment that they had to navigate through and were instructed to move as quickly as they could from the point of origin to the destination. Participants were free to navigate the environment as they saw fit, with the only condition that every time they encountered one of the five decision points they only selected one of the two available options, such as taking a wide or a narrow alley, or an alley with hidden-spaces versus a clear, open alley (Park et al., 2012). In line with results from previous research into the relation between participant characteristics and high-risk environmental contexts, Park and colleagues found that females in their sample displayed greater sensitivity towards the risk of victimization compared to males, and that there were no differences for participants of different ages.

In a study somewhat similar to Park et al. (2012), Toet and Van Schaik (2012) compared the effects of signs of public disorder, such as litter, cameras, vandalism and car burglary, on fear of crime. Similar to Nee et al. (in press), these researchers explored the ecological validity of a virtual environment by examining whether responses in case of a real urban neighborhood would resemble those to its virtual counterpart. In this study, participants walked through either the virtual or the real neighborhood, which was either in an orderly state or which showed signs of disorder. The virtual environment was also either presented with or without a realistic soundscape. Respondents were to report signs of disorder they noticed during their walk and the degree to which these affected their emotional state and feelings of personal safety. Following their tour, they appraised the perceived safety and livability of the area. Toet and Van Schaik (2012) find that both in the real and in the simulated neighborhood, signs of physical disorder evoked associations with social disorder. Disorder did not inspire concern for personal safety in either the real or in the virtual environment. However, in the absence of sound, disorder compromised perceived personal safety in the virtual environment. Signs of disorder were associated with negative emotions more frequently in the virtual environment than in its real-world counterpart, particularly in the absence of sound. Also, signs of disorder degraded the perceived livability of the virtual, but not of the real neighborhood. Hence, Toet and van Schaik (2012:273) conclude, it appears that people focus more on details in a virtual environment compared to real environments.

Relevant limitations of VR

Although VR has existed since the 1960s (IJsselsteijn, 2005) and has made enormous strides in quality, ease of use, and applicability since, there are still numerous limitations associated with VR and its technology. These limitations merit discussion here as they can have significant consequences for research using this technology as a tool for data collection.

To create an effective VE in which presence takes place, a user needs to let go of the awareness and knowledge that the stimuli in the VE are in fact not real. This is termed suspension of disbelief (Waterworth & Waterworth, 2001). Therefore the VR should be designed in such a way that the threat of disruption of this suspension of disbelief is minimized. Once the suspension is broken, the user (partially) experiences the real world and the technology used to create the VE instead of feeling present in the VE, which can negatively influence the intended effects of research. There are multiple possible causes for breaking the suspension of disbelief.

A first factor regards the technology used. Many VR devices are still rather cumbersome, hard to use and uncomfortable to wear (Ames & Wolffsohn 2005). This obtrusiveness means that the longer a user is in the VE, the higher the probability that the equipment will pull him/her out of it psychologically.

Second, the quality of virtual stimuli can negatively affect the experience of presence in the VE. Many head-mounted-displays offer a relatively low resolution (images appear pixelated or blurred) and a small field of view limiting the natural angle of view (McMahan, 2012; Riva, 2003), creating the impression of looking at a screen instead of feeling immersed in the VE. This influences the level of perceived realism and can lead to inconsistencies that cause the disruption of the suspension of disbelief. Many VR devices also suffer from lag between a user's input and the feedback to the VE, which negatively impacts presence and endangers the suspension of disbelief (Riva, 2003). This is also the main cause of so-called cybersickness (Schuemie et al., 2001; So et al., 2001). Cybersickness is the general term used to describe physical unease due to discrepancies between the internal expectations of the user and the actual VR feedback, e.g., a delay between the user's head movement and the visual feedback from the VR. Symptoms can vary from motion sickness, to ocular strain, and degraded limb and postural control (Ames & Wolffsohn 2005; Mantovani et al., 2003; Riva, 2003; Schuemie et al., 2001).

Third, the content of the VE can cause the breaking of the suspension of disbelief (Waterworth & Waterworth, 2001). Virtual landscapes, objects, and avatars should all be consistent with, and fit within, the visual and interactive design of the VE. A clearly or even subtly wrong object in an otherwise realistic VE will look out of place and therefore be a possible source of disruption of the suspension of disbelief.

Finally, a user's earlier experience with modern video games or VEs plays a role in the acceptance of VEs and their efficaciousness (Schuemie et al., 2001). Currently, there are large differences between individuals as some people have extensive experience with VEs whereas others only have very little experience. Perceived advanced technology can easily lead to problems in acceptance and even to fear of using it (Otte & Hoorn, 2009), thereby negatively affecting the suspension of disbelief.

VR equipment available on the consumer market

Setting up a high quality VR system used to be both expensive and time consuming. Tracking systems, graphics servers, custom-built rendering software, and devices such as head-mounted displays, required high levels of expertise and large investments. Nowadays setting up a VR system with a reasonable to high quality that is well suited for conducting scientific research is considerably easier and does not require a large budget. There are still costs involved and skills required to create a VE (Ausburn et al., 2004), but this has moved to well within the reach of the average university research department. As Ticknor and Tillinghast (2011) note, setting up a basic semi-immersive system roughly equals the cost and technical expertise needed to set up a new computer work station. Furthermore, a clear benefit of contemporary VR systems is their re-usability (Das, et al., 2005, Sims, 2007). Not only is hard- and software often application independent, but virtual objects, and in many cases also programming code, are easy to re-use in other VE setups.

In the remainder of this section, we provide a brief overview of some of the equipment, both software and hardware, necessary to set up a VR system and give several examples of the equipment that is available on the consumer market.

Software

First of all software is needed that facilitates the creation of the VE and renders the output from the computer back to the monitor or, in the case of immersive VR, a head-mounted display. Such a system should conform to several criteria to be usable for (non-technical) researchers. Both ease of use and cost effectiveness are important. Operating the system should be relatively easy to learn, it should be compatible with many input formats and it should use a relatively easy programming language. If possible, the system should be free of charge for academic use and still offer enough features to satisfy the quality and complexity needed for the planned study. Furthermore a large and active user community can be a significant advantage for acquiring assets and help. Finally output to several platforms (eg. PC, Mac, mobile devices, etc.) should be considered depending on the needs of the researcher.

There are many tools available on the consumer level and often at low cost, sometimes even free of charge, such as Unity[e], Unreal Engine[f], and CryEngine[g]. All of these tools are affordable, relatively easy to learn, and can achieve impressively high quality of imagery, provided the hardware can handle it and the user is skilled enough. These tools are not always developed to create 3-dimensional (3D) objects (although some object creation is often possible), but instead to set up the environment using pre-made 3D objects, lighting, define movement, and foremost establish program interactivity. To create 3D objects, a 3D modelling program is better suited, such as 3D Studio Max or Maya (Autodesk[h,i]). These programs are available free of charge to academic staff and students, but do require a significant amount of time to learn. Creating 3D objects is a skill in its own right and most users opt for downloading ready-made 3D objects from the Internet and using 3D modelling programs to fine-tune these objects, which can then be imported in tools like Unity.

Another open-source alternative is the NeuroVR platform[j] developed by Riva and colleagues for use in clinical settings. The NeuroVR Editor of the platform allows non-expert practitioners and researchers to modify and individualize a VE using an extensive database containing 2D and 3D objects. A player allows users to navigate and interact with the VEs that were created with the editing programme. The platform can be used in immersive and non-immersive ways and runs on standard PCs using Microsoft Windows and an upgraded graphics card (Ticknor and Tillinghast, 2011).

Although the quality of 3D objects is important, to achieve a high level of realism of the VE, the so-called textures are often even more important. Textures are attributes of objects that consist of one or more bitmap images that are applied over the 3D object and define the visual properties of that object. Most objects have at least one image that defines its colors, but other specially constructed images can convey the notion of surface texture (bumpiness), transparency, reflectivity, shininess, etc. To create these textures a bitmap editing program, like Photoshop (Adobe[k]), is required. Therefore the creation of a VE demands a modest level of experience with bitmap editing programs to create textures. For editing existing 3D objects in a 3D modelling program intermediate experience is needed, while a high level of expertise is needed to create 3D objects from scratch. Finally, an intermediate level of knowledge of working with 3D platforms like Unity is needed as well as intermediate programming skills to add interactivity and autonomy to the VE.

Depending on the level of experience of the researchers, it might be argued that setting up an interdisciplinary research team including people with programming and 3D modelling experience (e.g., Computer Science department) would benefit the overall quality and efficiency of the project.

Hardware

Although most modern computers are capable of running compiled VEs, a high-end PC with enough internal memory and a fast graphics card is a prerequisite for creating a VE. For the most basic forms of VR a standard computer monitor suffices. The user can interact with the VE through the use of a keyboard and a mouse or game controller. For more immersive virtual realities a tracking system and a head-mounted display are needed. As was mentioned earlier, tracking systems provide the VR software with information about the movement and position of the user. This information is used to render subsequent video and audio so that the user receives the correct feedback. The most affordable tracking systems use relative positioning and are less suited for free real world movement over larger spaces as they often suffer from cumulative errors in absolute positions. Most of these are so called Inertial Measurement Units (IMU). These systems measure movement by using a combination of accelerometers, gyroscopes, and sometimes magnetometers. An IMU is small, reasonably accurate and affordable and can be used in setups where the user does not physically move around and only tracking of the head is of real importance. More accurate tracking systems use optic, magnetic, or sonic signals to sense where one or more wearable active or passive tags are to locate the user and his/her orientation in the real world space. These systems are much more expensive and harder to install and maintain, requiring significant expertise and investment.

Head-mounted displays are available in many different configurations. Simple video glasses, primarily meant for viewing movies, can function as head -mounted displays. Their display quality and field of view (FOV) tend to be low, however, making them less suitable for immersive VR setups. Their low cost ($200-$500) do make them ideal for testing purposes. At the top end of the available head-mounted-display systems are devices that have a large FOV (120 degrees or more in horizontal direction and 45 degrees or more vertically) and offer high resolution. These systems usually suffer from two important drawbacks. They are often bulky and uncomfortable to wear for longer periods of time and their costs are in most cases prohibitively high ($50,000 or more). Through crowd funding initiatives other solutions are currently appearing on the market, which offer not only sufficient resolution and FOV, but also remain affordable and comfortable to wear. The best example at the moment is the Rift display from Oculus[l]. Although still under development, this system has all the characteristics of high-end systems, but at a fraction of the cost ($300). Systems like the Oculus Rift also have built-in IMUs for tracking head movements.

To further enhance immersion and presence, a VR system can be extended by using additional devices that create more affordances inside the VE. Examples include treadmills (e.g., the Virtuix Omni[m]) that allow the user to "walk in place" and cross unlimited virtual distances without moving in the real world, VR gloves (e.g., the DG5-VHand glove[n]) that allow for the tracking of hand and finger movement, allowing users to grasp and manipulate virtual objects, and motion capture systems that allow for the tracking of multiple points of the body allowing for full body simulation inside the VE. More exotic examples include scent devices (Nakaizumi, et al., 2006; Yasuyuki et al., 2005), like the AromaJet[o] and tactile feedback systems (Scheibe, et al., 2007, Deligiannidis & Jacobs 2006), like the InerTouchHand[p].

Conclusion

In this article, we have intended to provide criminologists with a fundamental understanding of VR and how it can be applied in research to advance our understanding of crime. The studies we discussed demonstrate that the manipulation of different characteristics of a VE can have significant impact on the user, both psychologically and physiologically, which makes VEs very suitable for research aiming to better understand criminal behavior. Not only do these features of VEs have immediate effects within the environment, but effects have been shown to also carry over into the real world in different behavioral domains, implying that VEs also have the potential to become powerful tools in the applied realm (Fox et al., 2009:100) and for changing delinquent behavior. The application of VR in the context of offender rehabilitation is an example that readily comes to mind in this respect.

All things considered, we think that VR has tremendous potential for crime research and that we are currently at a point at which it can be applied also by those who are not extensively schooled in computer technology and who do not have extensive programming skills. Furthermore, recent advances in the technology have made more equipment available at the consumer level, which has also greatly expanded the possibilities for using it in criminological research. Moreover, whereas immersive VR still requires specialized equipment, this is not the case for non-immersive VEs as most people nowadays have at least one and probably more devices to display them on such as notebooks, tablets and smartphones. This means that this type of VE has much potential to collect data also at remote or relatively inaccessible places. Additionally, both online VEs, such as Second Life, and offline VEs can generate vast amounts of standardized statistical data in a nonintrusive manner that can be used for analysis (Bainbridge, 2007; Fox et al., 2009). Scripts for IVR can be written to automatically record the user's movements, gaze and gestures which do away with the need to have coders review a videotape to code behavior.

We think that certain recent developments such as the acquisition of Oculus by Facebook[q] show that the momentum of more generally applied VR is increasing. Already the gaming industry is scrambling to include 3D and VR options in their next video game titles[r]. The effect of this will be, something that can be observed already at present, that hardware will become more affordable, of higher quality, and more userfriendly. Head -mounted displays will become lighter, easier to wear, wireless, and have high (HD) to very high (4kHD) resolution so that the equipment will no longer be a threat to VE experience.[s] At the same time, end-user software will start to incorporate 3D functionality, starting with video games[t]. We believe that the total effect of these developments will be that 3D VR technology will become ubiquitous and therefore also more easily available for research purposes. Because more applications will have 3D and VR capabilities, it will become easier for researchers to create VEs for their own research without needing special equipment or knowledge.

As was argued in this article, VR provides not only enhanced possibilities for improving existing methods of data collection, such as the vignettes used by deterrence and criminal decision making researchers, it also provides possibilities for the study of phenomena that are for practical, financial or ethical reasons impossible to study using other methods, such as burglary at the moment it takes place or situations involving large crowds. Additionally, the experimental control–mundane realism tradeoff, a main methodological problem in experimental research, can be overcome by VR technology as it combines high degrees of realism with high experimental control (Blascovich et al., 2002:103). Finally, on a more applied note, we wholeheartedly agree with Ticknor and Tillinghast (2011:4) who argue that "[w]ith dwindling budgets and swelling jail and prison populations, the criminal justice system stands to benefit from using technology that has provided positive outcomes in many other fields (…). By using virtual reality, researchers and practioners are able to create diverse environments that are safe, cost-efficient, and easy to control. The criminal justice system can incorporate this technology, along with conventional methods, in order to improve in the areas of research, training, and rehabilitation." We sincerely hope the criminological community will capitalize on these possibilities and start applying VR in its research agendas.

Recommended reading

Blascovich et al. (2002). Immersive virtual environment technology as a methodological tool for social psychology. *Psychological Inquiry, 13,* 103–124. Explains how IVR can solve different problems of experimental (social psychological) research: the experimental control–mundane realism trade-off, lack of replication, and unrepresentative sampling.

Burdea, G. C. & Coiffet, Ph. (2003). *Virtual Reality Technology*. Hoboken, NJ: Wiley Interscience. Provides an (technical) overview of VR technology. It is designed as a textbook on the subject of virtual reality and provides coverage of the technology—where it originated, how it has evolved, and where it is going.

Fox, J, Arena, D, & Bailenson, JN. (2009). Virtual Reality: A survival guide for the social scientist. *Journal of Media Psychology, 21,* 95–113. Provide nontechnical reader with a fundamental understanding of the components of VR and the role VR has played in social science. Reviews the literature and provides a comprehensive outline of social scientific studies using VR technologies.

Ticknor, B, & Tillinghast, S (2011). Virtual reality and the criminal justice system: New possibilities for research, training and rehabilitation. *Journal of Virtual Worlds Research, 4,* 3–44. Explains how criminal justice systems can benefit from VR by improving research methodologies, providing benefits to practitioners and offenders, and improving rehabilitation efforts.

http://www.vrs.org.uk Online resource with information about virtual reality and its components (e.g., apps, immersion, interactivity, therapies using VR, history, etc.).

Endnotes

[a]*Avatars* are controlled by a human user, whereas *agents* are controlled by an algorithm (Fox et al., 2009; see also the contribution of Gerritsen in this special issue for more information on agents and simulation studies and the 2008 special issue on Simulated Experiments in Criminology and Criminal Justice of the Journal of Experimental Criminology). When a virtual human is controlled by an algorithm, it is referred to as an *embodied agent* (Fox et al., 2009). This distinction is worth noting here because people tend to react differently when they believe they are interacting with an avatar; their physiological responses and behaviors tend to be more similar to how they would interact with a real person (Fox et al., 2009).

[b]An alternative IVR set-up involves the placing of multiple large projection screens (and loudspeakers) around and below a user, generally referred to as a CAVE or Computer Assisted Virtual Environments (Loomis et al., 1999).

[c]Vignettes or scenarios are short, generally written, descriptions of hypothetical situations. Participants are asked to read the vignette or scenario, to imagine him-/herself to be in the described situation and subsequently answer a number of questions pertaining to it

[d]Currently, the work by Nee and colleagues is being followed up in the Virtual Burglary Project, a collaboration between CRIME Lab at the Netherlands Institute of Crime and Law Enforcement (NSCR), the Network Institute -Tech Labs at the VU University in Amsterdam, and the the Faculty of Psychology of the University of Portsmouth. In this project, an entire virtual residential neighbourhood is being developed in which houses can be burglarized. This more sophisticated environment can be used to study a large variety of research questions, such as considerations of target choice, deterrence, guardianship and disorder but also more fundamental questions, regarding how offender characteristics such as self-control and sensation seeking influence how offenders actually go about committing their crime and how the criminal event exactly unfolds. Furthermore, perceptions of risk can be measured on a continuous basis by measuring heart rates and galvanic skin responses during the virtual burglary event.

[e]http://unity3d.com

[f]http://www.unrealengine.com

[g]http://www.cryengine.com

[h]http://www.autodesk.com/products/autodesk-3ds-max/overview

[i]http://www.autodesk.com/products/autodesk-maya/overview

[j]http://www.neurovr2.org/

[k]http://www.adobe.com/products/photoshop.html

[l]http://www.oculus.com

[m]http://www.virtuix.com

[n]http://www.vrealities.com/products/data-gloves/dg5-vhand-glove-3-0

[o]http://www.aromajet.com

[p]http://ap.isr.uc.pt/?w=project_information&ID=71

[q]https://www.facebook.com/zuck/posts/10101319050523971

[r]Tracking systems will remain somewhat of a problem because the required full immersion means full-body tracking and there is little indication that easy to use full-body tracking technology is around the corner. Systems like the new XBox Kinect do offer a lot of flexibility and advanced tracking possibilities, and could offer tracking solutions that are usable in research. Another partial solution to tracking are treadmill systems that allow users to move inside the VE whilst remaining in one place in the physical world. These are also seeing some new developments towards affordable and usable systems that can be used in research like the Virtuix Omni system.

[s]http://www.riftenabled.com/

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Received: 26 June 2014 Accepted: 11 September 2014
Published online: 11 November 2014

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doi:10.1186/s40163-014-0010-5
Cite this article as: van Gelder *et al.*: Using virtual reality in criminological research. *Crime Science* 2014 **3**:10.