Goggles in the lab: Economic experiments in immersive virtual environments

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Abstract

This review outlines the potential of virtual reality for creating naturalistic and interactive high-immersive environments in experimental economics. After explanation of essential terminology and technical equipment, the advantages are discussed by describing the available high-immersive VR experiments concerning economic topics to give an idea of the possibilities of VR for economic experiments. Furthermore, possible drawbacks are examined, including simulator sickness, the costs of VR equipment and specialist skills. By carefully controlling a naturalistic experimental context, virtual reality brings some field into the lab. Besides, it allows for testing contexts that would otherwise be unethical or impossible. It is a promising new tool in the experimental economics toolkit.

Keywords: virtual reality, experimental economics, high-immersive virtual environments, laboratory methods

JEL Codes: B41, C91, C93

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1 Introduction and terminology

Virtual Reality (VR) is a popular new technology by which almost any environment can be simulated and projected in 3D to the user. The rapid growth of VR is in large part driven by technological innovations and a sharp decline in the costs of VR devices. While VR as a research tool is now commonly applied in psychotherapy (Dibbets and Schulte-Ostermann, 2015), engineering (Freeman et al., 2016), spatial planning (Natapov and Fisher-Gewirtzman, 2016) and social psychology (Bombari et al., 2015), to date there are very few VR experiments in economics. Yet, the possibilities are promising: VR could add crucial realism to lab experiments and more control to field experiments. A recent review by Innocenti (2017) discussed how VR experiments may contribute to the field of economics by offering context to check the external validity of economic theories, with a focus on low-immersive virtual environments such as online virtual worlds. The current review does not address these low-immersive virtual worlds, but focuses on high-immersive virtual reality.

Recent reviews have highlighted the potential of VR for marketing (Barnes, 2016) and business research (Meißner et al., 2017). The current review complements by offering a critical overview of the possibilities and challenges for experimental economics in high-immersive virtual environments. The remainder of this article is organized as follows: Section 2 explains the essential terminology and technical equipment. Section 3 discusses the main advantages by describing the available VR experiments concerning economic topics to give an idea of the possibilities for economists, including an overview of relevant VR experiments in Table 1. In Section 4 possible drawbacks are discussed, including simulator sickness, the demand for physical equipment and specialist skills. Finally Section 5 provides some practical advice and Section 6 concludes.

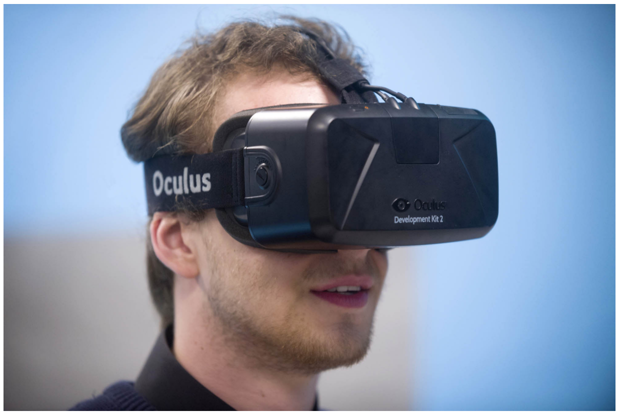
2 Terminology

The possibility to escape the world by virtually going elsewhere has always triggered human imagination. In the 1990s, this idea of creating a virtual world was first introduced in science, when communication researchers started to study virtual reality as a medium (Biocca and Levy, 1995). Virtual reality includes a computer generated environment and an interaction aspect. The Oxford English Dictionary defines VR as "the computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors" (Oxford Dictionaries, 2018).

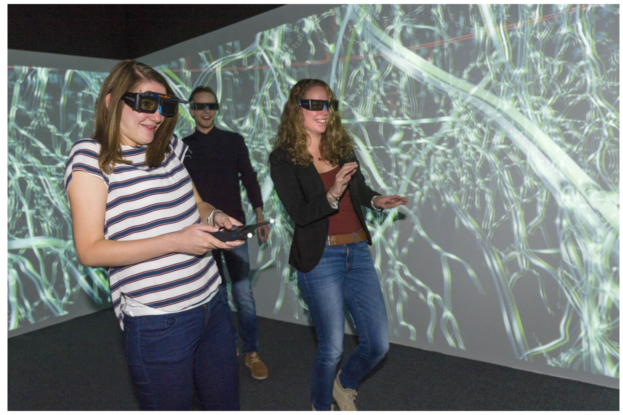
Several definitions describe how 'real' participants experience virtual reality. Following Bombari et al. (2015), in this review the term "presence" is used to describe the "subjective feeling of 'being there' and interacting with one's body in a virtual world projected by VR technology". As technology improved, the possibility of having more than one person in a VR environment was created in many modern labs. Consequently, the term "copresence" was coined: "the feeling of presence together with other virtual humans" (Bombari et al., 2015, p.33). Two classes of virtual humans can be defined: those controlled by algorithms (agents) and those controlled by other humans (avatars) (Bailenson and Blascovich, 2004). Sometimes, participants respond differently to these two types of virtual humans, for example by keeping more distance to agents than to avatars (Bailenson et al., 2003).

"Immersion" is defined by Bombari et al. (2015) as "the objective amount and quality of the perceptual input provided to the participant through technology" (p. 3). Immersion can be increased by showing a participant's own limbs in the virtual environment, while movements are projected in real time. Thus, by varying the amount of perceptual input or technological capabilities of the VR system (immersion), participants will experience the environment either as more or less 'real' (presence). A more thorough discussion of the concepts immersion and presence can be found in the survey of Slater and Sanchez-Vives (2016). Innocenti (2017) defines two classes of virtual reality environments by level of immersion, where low-immersive virtual environments (LIVE) represent desktop renderings and (online) virtual worlds, such as Second Life and World of Warcraft. The focus of this review is on the other class: high-immersive virtual environments (HIVE), where a virtual environment is projected in 3D to the user at the cost of more complex and expensive equipment.

VR equipment for HIVE falls into two broad categories: head-mounted displays (HMD) and projection screens, where the latter type is sometimes called a CAVE activated virtual environment (Cruz-Neira et al., 1993). Figure 1 depicts the two categories in the DAF Technology Lab at Tilburg University. An HMD brings the virtual environment close to the eyes of the participant, leading to a wide-angle view, including the virtual ground and ceiling. A set-up with projection screens in



(a) HMD



(b) CAVE

Figure 1: Different categories of VR equipment[1]

combination with stereoscopic glasses (CAVE), gives participants the freedom to walk around in the virtual environment and to enter the environment with multiple users. The downside to this setup is that the floor and the ceiling are often not used as projection screens, such that the borders of these areas are clearly visible, creating a less immersive environment.

In addition to virtual reality, two frequently used terms in both industry and academia are augmented reality (AR) and mixed reality (MR). Where VR excludes the real world almost completely from the (mainly visual) senses, in AR the physical environment is visible but overlaid with extra (computer graphic) information. MR adds interaction to the computer graphic objects projected by AR. Examples of modern-day AR/MR devices are the Google-glass[2] and the Microsoft Hololens.[3] This review focuses on high immersive virtual reality.

An important concept in VR is (virtual) embodiment, which refers to substitution of the real body by a virtual body (see Slater and Sanchez-Vives, 2016, for a survey of work on embodiment). Under the right technical conditions (perfect visuomotor synchrony, among others) embodiment can lead to the illusion of body ownership. Even though a person's own body might look very different from the virtual projection, the illusion can lead to a strong feeling that the virtual body is the real one. Embodiment allows for changing the virtual body, for example as an avatar that is taller (Yee and Bailenson, 2007), skinnier (Fox et al., 2009) or with a different skin color (Peck

[1]Pictures taken at the DAF Technology Lab at Tilburg University, retrieved from: https://www.tilburguniversity.edu/campus/experiencing-virtual-reality/.
[2]https://developers.google.com/glass/.
[3]https://www.microsoft.com/microsoft-hololens/en-us/.

et al., 2013) than subjects' appearance in reality. A related term is the 'Proteus effect' of Yee and Bailenson (2007), meaning that self-representation is modified in a meaningful way, which leads the user to conform to the modified self-representation regardless of the physical self. Fox and Bailenson (2009) found that participants exercised more when they saw a virtual representation of the self that changed in body weight in accordance to exercise efforts, than participants without a responsive representation.

Transformed social interaction refers to interpersonal communication in VR, where the appearance or ability of a participant has been changed. This includes possibilities that do not exist in the real world, such as changed perceptual abilities, forced perspective taking and controlled self-representation (Bailenson et al., 2005). For instance, Yee and Bailenson (2007) examined the effect of the height of avatars on negotiation behavior in an ultimatum game and found that participants with taller avatars behaved more confidently and proposed more unfair allocations than participants with shorter avatars. One could also change the appearance (e.g. height) of all other avatars in the virtual environment. Changing the communication itself can be achieved by manipulating the gaze of avatars, for example by shorter or longer eye contact (Bombari et al., 2015).

3 Advantages

Virtual reality experiments offer unique advantages to experimental economists, including the combination of experimental control and increased naturalistic context. Some of the most recent VR publications concern topics relevant in economics, such as helping behavior, cheating behavior and real-effort tasks. This section discusses these advantages by describing the available VR experiments concerning economic topics to give an idea of the possibilities of VR for economic experiments. A more complete overview of recent virtual reality experiments can be found in Table 1. The table shows only high-immersive VR experiments, although some desktop experiments are described in the paragraphs below for their innovative research design and their possibility to be extended to more immersive VR equipment. Another possible direction of experimental economic research is the execution of field experiments in on-line virtual worlds, such as World of Warcraft and Second Life. The present review does not concern these low-immersive virtual worlds, but a recent discussion can be found in Innocenti (2017), who argues that VR experiments (both low and high immersive) can be classified as framed field experiments.

3.1 Experimental control

One of the important advantages of virtual reality is its high level of experimental control. Outdoor environments can be tested without problematic interference of unintended contextual cues such as sound, smell and weather. Moreover, as Fox and Bailenson (2009) phrase it: "VR can be used to create stimuli that are unavailable or difficult to manage in the real world, such as large crowds, snakes, or children" (p.101). Using VR in addition to traditional lab or field experiments could solve the lack of exact replication in the social sciences that some researchers consider problematic (Blascovich et al., 2002; Rebelo et al., 2012). Furthermore, VR can offer high standardization in contexts that traditionally lacked it, such as social interaction. For example, Slater et al. (2013) used the standardization possibilities of VR to examine in-group versus out-group behavior. In particular, the authors studied the beliefs of 40 Arsenal[4] supporters about the relationship between victim and perpetrator in a violent pub situation. An argument was simulated between a victim wearing a football-shirt/Arsenal-shirt and the perpetrator. The victim was programmed to look at the participant in some of the conditions. The results show that in-group participants (i.e. Arsenal supporters watching an Arsenal fan being attacked) were more likely to intervene in the conflict than out-group participants. From this in-group, those who believed that the victim was looking at them, intervened more than those who did not believe they were looked at.

Qu et al. (2015) studied a different aspect of social interaction with the help of virtual standardized humans: the effect of bystanders in a classroom setting with a within-subject design. 26 participants were asked to take part in a virtual language lesson where their virtual classmates where whispering either approvingly or skeptically. As a result, participants' self-reported beliefs, self-efficacy and anxiety levels shifted. Furthermore, beliefs about the teacher (whose behavior was in fact always neutral) varied as well, leading participants in the negative-comments condition to think that the teacher disapproved too. On the other hand, participants gave longer answers in the case of positive whispering classmates, which correlated with a lower self-reported level of anxiety.

Recently, Mol et al. (2018) studied the effects of a virtual observer on cheating in a VR version of the mind game, which is a variation of the die-under-the-cup paradigm. In this game, subjects

[4] I.e. the football club.

had the incentive to be dishonest by reporting the highest payoff, without the chance of getting caught. A VR agent as observer allowed for a more naturalistic variation of observability than the typical images of 'watching eyes' in the literature on social control. They found similar levels of cheating as in the conventional lab equivalent of the mind game. The presence of the virtual observer did not affect cheating, compared to the same VR environment without a virtual observer. However, participants cheated significantly more when the virtual observer was passively seated in a corner, rather than actively staring at the participant. The authors discuss the impact of human-like virtual observers on cheating behavior, which involves more than simple cues of social control. Note that using VR experiments eliminate the need of confederates, an experimental practice using deception, which is generally disapproved by economists (cf. Hertwig and Ortmann, 2001; Ortmann and Hertwig, 2002).

3.2 Experimental realism

In the past decades, economic experiments were not only used to test theories, but also to motivate and develop new theories, which makes the external validity of experiments more essential (cf. Schram, 2005). The highly naturalistic situations participants experience in a VR experiment can generate more natural responses than traditional lab experiments (Fox et al., 2009). By visualizing life-like situations, emotional arousal can be elicited to the extent that post-traumatic symptoms may be reported. Dibbets and Schulte-Ostermann (2015) used VR to induce a mild trauma (a scene about physical abuse) upon participants and found a large degree of presence and immersion, as well as traumatic symptoms in the week after the view.

Participants can thus be confronted with decisions in a more natural way (naturalistic cues) than via conventional ways such as vignettes, scenarios and self-report questions. The scenario-approach is typically low in ecological validity: asking participants what-if questions requires them to imagine the situation, where the quality of imagination can never be controlled. Virtual reality allows for the careful controlling of perception confounds, by showing participants the context of the question. This way, participants have no need to 'bring' their own frames or life experiences to the game (see Harrison et al., 2011, for a careful discussion on this topic). For example, DeHoratius et al. (2018) used a virtual conveyor belt as an environment similar to the work environment of many retail employees to study the effect of packaging and similarity on sorting errors. Their results have clear implications for retailers who wish to improve employee productivity, for example by adding visual cues. Haruvy et al. (2017) also take advantage of rich contextual cues to study the effect of communication and visibility on contributions in a public goods game. The authors contrast an abstract zTree environment with a 3D avatar-based virtual world and find that communication improves contributions in both environments, but that communication and visibility are complements in the virtual world.

Besides, the high degree of experimental control in VR allows for repeated viewing of the same or slightly different environments, which is one of the reasons that VR is applied in the treatment of phobias (Wiederhold and Bouchard, 2014). In economics, this gradual change of environments can be used to study preferences that are hard to imagine, for example in the domain of risky and dangerous decisions. The outcomes of hypothetical risky decisions, such as damage due to (natural) disasters and accidents might be visualized. Research from psychology shows that VR exposure might change participants' risk perception, depending on the VR environment (Chittaro et al., 2017). Furthermore, VR allows for detailed studies on subjective probability formation based on simulated environments, in contrast to abstract lab experiments based on simple objective probabilities that are not so common in the field (Harrison et al., 2015). As there is considerable heterogeneity in risk attitudes across elicitation methods and domains (Csermely and Rabas, 2016; Pedroni et al., 2017), such rich visualizations of (compound) risk and uncertainty might be of interest to economists. Using an environment that is very close to the natural environment in which people make decisions, while controlling for perception confounds, is a new type of experiment that could add valuable contributions to experimental economics.

Furthermore, the higher level of presence that can be achieved by VR, in comparison to mainstream photos or videos, may enhance emotions, empathy or altruism. 360° VR videos can be used to induce stronger emotions in participants than conventional methods such as images or 2D video (Diemer et al., 2015; Schutte and Stilinović, 2017). Many researchers have shown that emotions can alter decisions in economic contexts (Fiala and Noussair, 2017; Martinez et al., 2011; Lin et al., 2006). In a recent experiment, Gürerk and Kasulke (2018) presented participants with a real effort task to earn their endowment, which they could donate later to a local refugee organization. Before donating, participants viewed a 360° video of the destroyed city of Aleppo in Syria on a computer screen or a VR version in a HMD. A control group watched no video at all. Besides the donation decision, the researchers measured empathy with the Interpersonal Reactivity Index questionnaire. They found the highest scores in the VR treatment, both for empathic concern as for donations. These results are in line with the findings of Schutte and Stilinović (2017); greater engagement and higher reported empathy by participants in the VR condition compared to the control condition where a documentary on a refugee camp was presented in 2D format. Another illustrative example is provided by Kugler et al. (2018), who used HMDs to induce disgust emotions in participants, to study the effect on trust in an economic trust game. They find that disgusted participants are less trusting, presumably because they misattribute their emotions to the course of the game.

It should be noted that a rich and natural set of stimuli or context that can be provided by VR is not useful for all domains of economics. Many economic experiments are mainly abstract and neutrally framed and it is not the aim of this review to change such good practice. However, in some domains VR could help to generate more stable decisions in complex environments.

3.3 Logging of responses

Another interesting feature of VR devices is the automatic logging of response data such as movement and rotation (Parsons, 2015), which can be captured in detail depending on the hardware used. Gillath et al. (2008) for example, measured individual differences in helping behavior of a virtual person in need. In a first experiment, participants encountered a blind man in need (he lost his walking cane) on an urban side walk. Apart from self-report empathy measures, physical helping (approaching) responses were recorded and coded. The results showed that 30% of participants expressed their concern (either verbally or by offering help) when approaching the man, which is a similar measure as has been found in field experiments outside VR (Guéguen and De Gail, 2003). In a second experiment the blind man was replaced by either a beggar or a businessman. Gaze direction of the participant and distance to the man were measured by the HMD and the results from the first experiment were replicated. A different example of a VR study using detailed logging of response data, is Gürerk et al. (2019), who simulated a virtual conveyor belt and asked participants to sort pieces according to the color on one side of the blocks. The controllers used by the participants to rotate the blocks in the virtual environment allowed the authors to rate performance both on speed and accuracy, while manipulating the performance of a virtual co-worker in the background. The authors were able to "evaluate how subjects make the trade-off between quantity and quality as a function of the economic incentives provided" (p. 4). They found that competitive subjects perform better when working with a highly productive peer compared to when they work in the presence of a low-productive co-worker.

McCall and Singer (2015) also took advantage of the detailed logging of interpersonal distances by studying approach and avoidance behavior in a virtual environment. First, participants were asked to play a trust game twelve times on a desktop computer with two confederates (players A and C) as opponents (one fair and one unfair player). In the next stage, participants were immersed in a VR with two agents: players A and C. Participants were led to believe that these agents were avatars, controlled by the actual humans that they played the trust game with in the first stage. The task performed in VR was a memory task, while the dependent variable of interest was the distance between participants and the other players. In the last stage (outside VR) participants could punish the other player(s) by paying to remove tokens from another player. Participants came significantly closer to the fair agent than to the unfair agent. Interestingly, those participants who chose to punish considerably, spent more time in front of the unfair agent, which was interpreted as mildly aggressive behavior.

Overall, the potential of VR in the automatic logging of responses is considerable, as it offers new objective variables, such as gaze direction and hand rotation. It should be acknowledged that detailed movement tracking in itself does not provide added value to all economic experiments. Yet some topics, such as principal agent paradigms using real effort tasks, may benefit from the detailed analysis of time, position and visibility (DeHoratius et al., 2018). Note that the greatest precision in the measurement of human movement can be accomplished by the use of motion trackers, while an HMD or controller will yield only data on the head or the hand movement of the participant. Besides, eye trackers may be combined with VR hardware, which enables researchers to track precisely which information participants are viewing (Meißner et al., 2017). Future developments may improve automated interactivity, for example by simulating a corresponding responsive negotiator in front of the participant. Evidently, the recommended hardware selection depends on the specific research question at hand.

3.4 Visualizing complex questions

Virtual reality is frequently used to visualize complex problems in environmental science, as well as in landscape architecture (Patterson et al., 2017) and construction business (Portman et al., 2015; Pérez Fernández and Alonso, 2015). For example Patterson et al. (2017) used low-immersive VR to refine the coefficients of discrete choice experiments on neighborhood choice. Another complex environment that can benefit from VR experiments is transportation. Dixit et al. (2014) used virtual reality driving simulators to study the subjective beliefs of participants under different risky traffic scenarios, while controlling for experience and risk attitudes. They found that participants who crashed were generally more optimistic about their success in the task, although this was unrelated to risk attitudes.

Virtual reality allows for naturalistic exploration of large areas with multiple users simultaneously, which is useful for environmental scientists to study wild fire prevention (Fiore et al., 2009), land use change (Bateman et al., 2009) and coastal erosion management (Matthews et al., 2017). Bateman et al. (2009) performed a choice experiment on coastal land use both with and without a virtual reality visualization, while keeping the objective information presented constant. The VR visualization showed a smaller variability in elicited preferences and a smaller the willingness to pay (WTP) - willingness to accept (WTA) gap. Matthews et al. (2017) used virtual environments in a desktop choice experiment about coastal erosion managment. In line with the results of Bateman et al. (2009) the authors found a significant decrease in choice error and a different WTP in the virtual reality group as compared to the static images control group. Fiore et al. (2009) showed a VR visualization of forest fire consequences to study individuals' assessment of risks of prescribed burns, in comparison to a multi-image visualization of the consequences. A multiple price list was used to determine subjective beliefs of the subjects with regard to the risk of the simulated forest fire. The results showed that the subjective beliefs in the VR visualization treatment were closer to the actual risks than the subjective beliefs in the image treatment. The authors conclude that the primary benefit of VR is the naturalistic way in which counter factual scenarios can be generated. This is particularly important in environmental issues, where individuals often have difficulty with the comprehension of possible consequences in the long run, for example in assessing the effects of global warming.

In a follow up study, Harrison et al. (2015) studied the relationship between prior experiences and perception formation in natural risky decision settings by forest ranger experts and non-expert residents. They found that experts are focused too much on prior beliefs and therefore do not outperform non-experts in estimating compound risks.

3.5 Conducting "impossible" experiments

One of the unique advantages of virtual reality is that it gives the experimenter the freedom to test situations that would never be possible in the real world. For example, Rosenberg et al. (2013) offered participants the ability to fly over a virtual environment, after which they measured the degree of helping. They found that participants who were able to actively fly in the VR environment (as opposed to the control group, who were seated in a virtual helicopter) picked up more pens in a subsequent helping task. Gamberini et al. (2015) manipulated the ethnicity of the victim in different emergency situations (*None* versus *Time pressure* versus *Fire*). The experimenters sent participants into a virtual building with the assignment to leave the building after exploring it. Suddenly, a screaming voice asked for help from the cafeteria inside the virtual building. In addition to the binary variable helping (defined as moving back to the cafeteria before moving to the emergency exit), the researchers registered promptness, number of collisions with the walls and number of backward movements. They found that 68% of the participants helped, but a significant racial bias was found (black victims were helped less often than white victims).

Other possibilities include experiments that would be unethical in the real world, such as showing the (fatal) results of a choice in a moral dilemma (see e.g. Navarrete et al., 2012, for the trolley problem in VR) or replicating the classic Milgram obedience experiment (Slater et al., 2006). Responses in risky situations can be trained repeatedly without exposing participants to unethical situations. Evacuation behavior can be tested experimentally with non-expert participants, for example in a virtual tunnel-fire (Kinateder et al., 2014) or during an earthquake (Lovreglio et al., 2017). Zaalberg and Midden (2013) exposed participants to a (desktop) VR simulation of a dike breach to test how flood awareness can be improved. The results showed that information search, evacuation motivation, and stated preference to buy flood insurance increased after the VR simulation compared to a film and slide show version of the dike breach.

A further promising approach is to use VR to visualize the future, thereby confronting participants with consequences of their behavior. This approach was tested successfully in the domain of exercise behavior, where participants were encouraged to exercise in response to a virtual future self who either gained or lost weight (Fox and Bailenson, 2009). The results showed that participants exercised more when they saw a virtual representation of the self that changed in body weight in accordance to exercise efforts, than without a responsive virtual representation. The same idea can be applied to inter-temporal choice to increase saving behavior, by showing participants a virtual construction of their elderly self. Hershfield et al. (2011) embodied participants in a virtual construction of an elderly self and let them through a mirror with their (visually) elderly body. After a short walk to get familiar with their body in the virtual environment, participants could watch their virtual body in a virtual mirror, which lead to increased saving behavior in a subsequent task. Interestingly, embodiment in another elderly person did not increase saving behavior. In a related experiment, van Gelder et al. (2013) used the same method to construct projections of participants (present self) and age-processed these (future self). The authors compared cheating behavior after exposure to either their present self or their age-processed future self and found that interaction with the future self significantly decreased cheating.

Table 1: Overview of papers using high-immersive virtual reality experiments

Publication	Research question	Dependent variable	Tool	N	Field
Bailenson et al. (2003)	What interpersonal distance do participants keep towards virtual humans?	distance	HMD	160	soc psy
Bailenson et al. (2005)	Do listeners show more agreement with a presenter who is gazing at them?	gauged social presence	HMD	72	comm
Slater et al. (2006)	To which extent do participants respond to an extreme social situation (Milgram) as if it were real, even though it is VR?	shocks administered, skin conductance, hr	CAVE	38	soc psy
Yee and Bailenson (2007)	Does behavior conform to a digital self-representation independent of how others perceive them?	ultimatum game	HMD	50	comm
Gillath et al. (2008)	What is the effect of context on helping? (businessman / beggar)	helping, empathy scale	HMD	107	psy
Fox and Bailenson (2009)	Can real-time vicarious reinforcement (avatar losing/gaining weight) improve exercise behavior?	exercise repetitions	HMD	189	clin psy
Hershfield et al. (2011)	What is the effect of age-processed renderings of future self on saving behavior?	choice task	HMD	103	eco
Latu et al. (2013)	Do successful female role models empower women's behavior in a leadership task?	speech length & quality	HMD	149	soc psy
Peck et al. (2013)	Can embodiment in a different skin color change racial bias?	IAT	HMD	60	soc psy
Rosenberg et al. (2013)	Does giving people superpowers in VR lead them to behave more prosocial in reality?	number and speed of pens picked up	HMD	60	soc psy
Slater et al. (2013)	Under what conditions will a bystander intervene to try to stop a violent attack by one person on another?	number of verbal and physical interventions	CAVE	38	soc psy
van Gelder et al. (2013)	Can exposure to a VR age-progressed self predict delinquency?	cheating (quiz)	HMD	67	crime psy
Dixit et al. (2014)	What is the impact of subjective beliefs of risk on driver safety?	virtual crashes	CAVE*	132	eco
Hadley et al. (2014)	What is the effect of risky cued VREs on physiological arousal?	hr, arousal	HMD	42	clin psy
Kinateder et al. (2014)	What is the influence of a peers on emergency route choice?	movement trajectories	CAVE	42	safety
Gamberini et al. (2015)	What is the effect of time and race on helping in VR emergency?	helping (binary)	HMD	96	psy
Kinateder et al. (2015)	What is the effect of dangerous goods transporters on hazard perception?	movement trajectories	CAVE	40	safety
McCall and Singer (2015)	Do physical movements (or interpersonal distances) in VR predict (financial) behavior outside VR?	distance, gaze direction	HMD	56	soc psy
Murray et al. (2015)	What is the impact of present others on exercise behavior?	distance rowed	CAVE	60	psy
Qu et al. (2015)	Can bystanders' judgments influence a person's beliefs, self-efficacy and emotions?	speech length, arousal, beliefs	HMD	26	edu
Toppenberg et al. (2015)	To what extent are diagnosis (HIV, cancer or broken leg) and sexual orientation related to approach behavior?	distance, speed, head orientation, IAT	HMD	49	soc psy
van Herpen et al. (2016)	Can real-life shopping behavior in a supermarket be captured in VR?	products selected	CAVE	100	marketing
Puschmann et al. (2016)	Can VR-based risk assessments offer an alternative to document-based or CAD-based approaches?	machine operation	CAVE	27	safety
Hale et al. (2017)	Can specific trust towards strangers be measured in a virtual maze task?	directions, advice	HMD	24	soc psy
Schutte and Stilinović (2017)	Can a virtual reality experience increase empathy?	empathy scale	HMD	24	psy
Chittaro et al. (2017)	What are the effects of a VR experience on risk attitudes?	hr, (risk) surveys	HMD	108	psy
DeHoratius et al. (2018)	Quantify the role of product similarity in execution failures	sorting errors	CAVE	87	eco
Gürerk and Kasulke (2018)	Does virtual reality increase charitable giving?	donations, empathy	HMD	61	eco
Kugler et al. (2018)	What is the effect of disgust emotions on trust behavior?	trust game	HMD	104	eco
Graff et al. (2018)	How do tournament incentives and peer effects interact in a dynamic setting?	real effort	CAVE	131	eco
Mol et al. (2018)	Can cheating be affected by the presence of a virtual observer?	cheating (mind game)	CAVE	121	eco
Gürerk et al. (2019)	What is the effect of the presence of a virtual co-worker on real effort?	speed, accuracy	CAVE	108	eco

Notes: Abbreviations used: comm = communication research, soc = social, clin = clinical, psy = psychology, env = environmental, eco = economics, edu = education science, hr = heart rate. * multi-screen driving simulator.

4 Challenges

While VR experiments as a research tool has many advantages, a number of challenges need to be addressed. The following section discusses the current state of affairs with regards to costs, specialist skills, simulator sickness, familiarity, naturalistic avatars and lab time.

4.1 Costs

The costs of a virtual reality lab can be divided into two categories: hardware and software. As mentioned before, different possibilities exist for the hardware set-up. In addition to the headset and controllers, many HMDs require a platform (e.g. desktop computer, smartphone) to render the virtual environment, although "standalone HMDs" are a recent addition to the VR hardware market[5]. The costs of an HMD set-up range from €10 (excluding smartphone) for the Google Cardboard[6] to the more expensive displays with a higher resolution and a larger field of view, such as the Samsung Gear VR[7] (€115, including one controller, excluding smartphone), the Oculus Rift[8] (€450, including two controllers) and the HTC Vive[9] (€600, including two controllers.). The most expensive VR headset at the time of writing is the Pimax 8K[10]. This headset can be purchased from €900 (excluding controllers) and offers a 200-degree field of view which comes closest to the 220-degree field of view of the human eye. Note that all devices try to strike a balance between costs, wearability and screen quality. Recent releases of new VR products have focused on improving screen resolution and field of view. A larger field of view could decrease simulator sickness susceptibility as it would require less head movement (Serge and Fragomeni, 2017). A larger screen resolution is desirable to increase immersion and thus presence, especially when it is detailed enough to remove the pixelated view known as *screen door effect*[11] that arises when the display is magnified in front of the eyes of the user. Solutions to the screen door effect are in development (Cho et al., 2017; Sitter et al., 2017) and might be implemented in the newest (business) releases of VR hardware. A recent discussion of screen latencies for both CAVE and

[5] For example Oculus Go (€250, https://www.oculus.com/go/) or HTC Vive Focus.
[6] https://vr.google.com/cardboard/get-cardboard/.
[7] https://www.oculus.com/gear-vr/.
[8] https://www.oculus.com/rift/.
[9] https://www.vive.com/eu/product/.
[10] https://pimaxvr.com/products/pimax-8k-vr-headset/.
[11] The term originates from the comparison to a view through a fine mesh as in anti-insect screen doors

HMD can be found in Meißner et al. (2017). Note that these technological advancements are costly and might increase hardware prices. Researchers who wish to purchase VR HMD equipment could compare the current HMD devices on computer magazine websites.[12]

The hardware set-up costs of a CAVE are considerably higher. Prices range from €5.000 for a 3D projection screen to €20.000 for a simple CAVE to €1.5 million for a complete CAVE including stereoscopic glasses, motion capture and sensing technology (Pérez Fernández and Alonso, 2015). Note that these prices are an indication and the VR technology market is constantly developing. Different hardware set-ups require different software. Most 3D scripting languages are interchangeable but caution is required when avatars are used in combination with motion capture: using the right skeleton[13] is crucial. Many of these programming applications are open-source software and therefore free to use while others are commercial, but academic subscriptions are available. Different software is necessary for each step in the process: from constructing the 3D environment (e.g. Autodesk 3DS Max, Maya, Sketchup) to texturing (e.g. Adobe Photoshop) and scripting (e.g. Unity, Unreal, Vizard). For a comprehensive overview of the process of developing a virtual environment, see Chapter 11.4 in Wiederhold and Bouchard (2014).

4.2 Specialist skills

One might fear that the construction of a VR environment requires specialist programming skills. In essence this is true but the accessibility of software (e.g. Vizard, Unity 3D) and assets has been greatly improved over the past decades. In the words of Fox et al. (2009): "a computer science degree is no longer necessary to understand and implement them (VE environments)" (p. 106). In addition, graphic simulations, avatars and 3D renderings can be found and bought on the Internet, where a specialist marketplace has been created in parallel to the developments in the gaming industry.

4.3 Simulator sickness

Probably the best documented negative side-effect of the use of VR equipment is simulator sickness, a type of motion sickness. During or after exposure to a virtual environment, a mismatch between

[12] See e.g. https://www.slant.co/topics/1668/~best-vr-headsets/.
[13] The basic joints structure to which different avatars and animations can be added.

vision and input of the vestibular system can cause symptoms such as nausea, blurred vision and instability (Rebelo et al., 2012). Simulator sickness seems to get worse in the case of a large display delay: a temporal delay between the physical movement of the participant and the updated screen. However, due to increased computational power, recent VR equipment is constructed to reduce the display delay to the minimum by maximizing the field of view and the refresh rate (Parsons, 2015). A larger field of view inside a HMD would require less head movement (Serge and Fragomeni, 2017), decreasing the likelihood of simulator sickness. Unsurprisingly, these technological advancements are a costly part of the VR hardware price. The severity of simulator sickness symptoms is further connected to the type of VR equipment, where HMDs may lead to more severe symptoms than projection screens (CAVEs) and desktop computers (Sharples et al., 2007). Practical experience from the DAF Technology lab at Tilburg University demonstrates that control over the navigation in the virtual environment decreases simulation sickness, while passive participants experience more simulation sickness. A recent test with 24 participants using the HTC Vive found no uncomfortably high sickness ratings on average (Serge and Fragomeni, 2017). Another recent study with the Oculus Rift found that some participants experience simulator sickness, but much depends on the type of game (Munafo et al., 2017). Particularly movements in the game that are not synchronized with real (bodily) movements are likely to cause simulator sickness, such as riding a virtual roller-coaster while sitting in a fixed (non-moving) chair."

Another parameter in the context of simulator sickness is exposure duration. Longer exposure tends to produce more symptoms (Stanney et al., 2003), although after approximately 60 minutes habituation can occur: participants will adapt to the new environment, leading to a decrease in symptoms. Habituation will increase by offering repeated (short) exposure periods. The availability of breaks can decrease the severity of simulation sickness (Rebelo et al., 2012) but it may have a negative effect on presence.

4.4 Familiarity

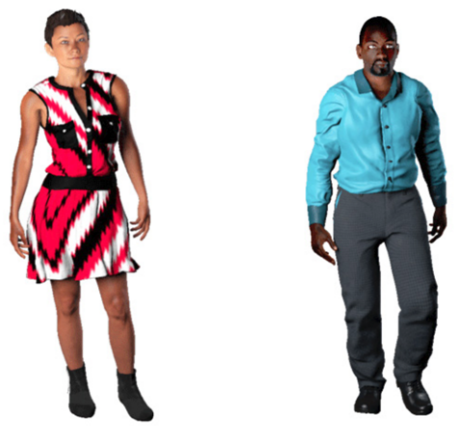
Some participants are more familiar than others with the usage of VR equipment, for example because they play 3D video games frequently. In rare cases this may cause a confounding factor in the analysis of the results. A few researchers have argued that individual differences in computer familiarity can indeed moderate the effect of VR interventions (Turner and Casey, 2014). However, little research has been performed to back up this claim. A self-report question about familiarity with video games and VR equipment may be asked in the post-experimental questionnaire to control for this effect.

4.5 Naturalistic avatars

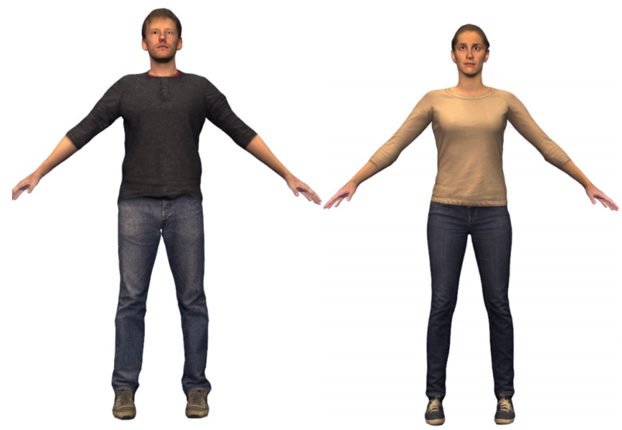
Social interaction in virtual reality requires avatars. While naturalistic avatars are not crucial to induce a feeling of interaction or embodiment, they have a powerful impact on presence. Detailed and naturalistic avatars demand computational power to render and more time to animate. VR software often comes with some free stock avatars (see Figure 2a) and extra avatars can easily be bought on-line. The quality of these avatars has improved over the past decade, although the face is difficult to model and each muscle should be animated. To circumvent this problem, one could consider to use avatars who do not face the participant, for example because they perform a task at the next conveyor belt (DeHoratius et al., 2018; Gürerk et al., 2019). Animations are available on-line, including many free ones (see Figure 2a). However, joining these animations and adding a certain movement path requires software skills. Alternatively, a motion tracker suit could record the animations, which gives very natural results but adds another hardware item to the VR startup costs[14]. Recent developments in the domain of motion tracking combine the data of several trackers (e.g. €120 HTC Vive Tracker) with motion capturing software[15] to track and model real-time full body avatars.

Note also that the focus of the gaming industry is mainly on fantasy characters, which leads to a large supply of monsters, soldiers and animé characters, while "normal" people are harder to find. A solution would be to create your own character[16], which gives the opportunity to confront participants with subtle variations in avatars, but comes at the expense of programming time and requires software skills. A recent technique is to make 3D scans of real humans, which results in a detailed and naturalistic avatar (see Figure 2b). Achenbach et al. (2017) present a 3D-scanning setup which takes less than ten minutes to complete, enabling researchers to scan each experimental subject prior to VR exposure.

[14]See https://www.rokoko.com/ (from €2.500) or https://neuronmocap.com/ (from €1.000).
[15]https://www.ikinema.com/full-body-ik-for-vr
[16]For example with Adobe Fuse: https://www.adobe.com/products/fuse.html/.
[17]Reprint courtesy of Latoschik et al. (2017).



(a) Animated avatars of Adobe Mixamo



(b) Avatars created with 3D scans[17]

Figure 2: Examples of naturalistic avatars

4.6 Lab time

In comparison to experiments in traditional labs with multiple workstations, VR experiments will require more time to conduct because there is often only one CAVE or HMD available, taking about 10 to 30 minutes per participant, sequentially. However, the costs (especially of HMDs) may decrease in the future and the set-up is not time-consuming, as it is with invasive biometric tools such as heart rate, fMRI and EEG.

5 VR in practice

Even though VR experiments offer the opportunity to increase external validity, that does not mean that it happens by design or without effort. Harrison et al. (2011) discuss some issues on both external and internal validity in the design of VR experiments, including perception confounds and sample selection. Some practical suggestions with regards to conducting a VR experiment are discussed below.

5.1 Ethical use of VR

As with any new technology, the use of virtual reality might pose risks that are yet unknown to its users. VR might not seem as invasive as several biometric methods, but it has the potential to have lasting effects (cf. Dibbets and Schulte-Ostermann, 2015). It is therefore strongly recommended to adhere to the *VERE code of conduct for the ethical use of VR in research* by Madary and Metzinger (2016) and to exclude vulnerable participants from the experiment. These at-risk participants include epileptic patients and patients with psychosis or personality disorders as they could possibly mix up reality with the virtual environment (Wiederhold and Bouchard, 2014). Most economists might not be handling a clinical population, but the recommendations on non-maleficence and informed consent are important for all disciplines.

5.2 Minimizing simulator sickness

Even though simulator sickness is not commonly reported with modern-day VR facilities, researchers take measures to mimimize and track potential sickness. Sharples et al. (2007) report several guidelines for VR researchers to minimize the negative effects of simulator sickness, such as giving participants control over their movement in the virtual environment (cf. Wiederhold and Bouchard, 2014). A further recommendation is to be aware of physiological signs of participants suffering from simulator sickness (sweating, pallor, fidgeting with HMD, closing eyes). VR researchers have developed different measures in order to track simulator sickness, including physiological measures such as EEG, blood pressure and heart rate. Still, the most widely used measure is a self-reported questionnaire, such as the simulator sickness questionnaire (SSQ, Kennedy et al., 1993). To prevent an experimenter demand effect, one might consider conducting only the post experimental SSQ (see Young et al., 2006, for a discussion on this issue). The SSQ has recently been revised by Balk et al. (2013) to update the factors with current technology and to examine dropout predictability. They conclude that the SSQ is "still relevant today" (Balk et al., 2013, p.263), and is therefore recommended for future VR research.

5.3 Measuring presence

Without a substantial level of presence, the benefits of a VR experiment compared to a conventional lab experiment could be neutralized. When a certain condition is clearly more engaging for participants than another, treatment effects might be confounded by presence levels. Thus, researchers may want to control for presence levels of participants. The traditional method to measure presence is with a self-reported questionnaire (c.f. Witmer and Singer, 1998; Schubert et al., 2001), although questionnaires are known to have limited stability (Slater, 2004). Most presence questionnaires use seven-point Likert Scales on questions such as *How aware were you of events occurring in the real world around you*, *How natural did your interactions with the environment seem* and *Somehow I felt that the virtual world surrounded me*. Slater (2009) distinguishes two types of presence: place illusion and plausibility. Place illusion refers to the physical feeling of being in the virtual environment, where plausibility captures the idea that whatever happens in the virtual environment is real, regardless of the knowledge that the virtual environment was constructed by technology. Subjects with strong feelings of plausibility would respond similarly in reality as in the real world. Considering that conventional presence questionnaires focus mostly on place illusion, Qu et al. (2015) developed a presence response scale to capture plausibility scores. Recently, Diemer et al. (2015) suggested that participants might judge their presence level based on immersion, as well as on emotional arousal. Thus, in certain emotional (e.g. fearful) situations, one might measure presence by physiological measures, such as galvanic skin response. A detailed discussion of measuring presence can be found in Sanchez-Vives and Slater (2005).

6 Conclusion

This review aimed to give a critical overview of the possibilities and challenges for experimental economics in high-immersive virtual environments. While VR is becoming more mainstream in disciplines such as engineering, psychology and spatial planning, VR experimental economics is still in its infancy. Some domains of economics could benefit from visualizing a rich and natural context that can be provided by VR.

One of the key advantages of VR above conventional field experiments is that it is relatively easy to control for confounding factors such as weather, gender and non-verbal cues. Many economic field experiments could be improved by this technology, leading to more robust findings and helping to exclude alternative explanations. Thanks to the improved technologies in the past decade, perceived realism (presence) now allows for VR research to move from methodological publications to experiments with respect to content and the objective measurement of human movement may offer new insights. Furthermore, experiences in VR seem to extend to real life and a close parallel has been found between behavior in VR experiments and conventional labs. By carefully controlling the context of an experiment, virtual reality could bring a bit of the field into the laboratory. VR experiments can be considered framed field experiments, as the context they provide to subjects is completely controlled by the experimenter (Innocenti, 2017). VR is a promising new research tool when it comes to visualizing complex economic questions. Future research with virtual reality could help to visualize those questions, such as belief elicitation, risk perception and preference, gain-loss asymmetry in environmental planning and inter-temporal choice. By helping people to visualize these situations, they might be better able to form stable beliefs and preferences. Other suitable topics include social interactions that are not easily controlled in field experiments and a detailed logging of responses. Social dilemmas may be presented much more naturally than in a conventional computerized experiment and games may be played with multiple players in the same VR environment. Alternatively, consider a VR physical real effort task (e.g. where subjects have to physically move many objects) to examine a response to incentives, where current real effort tasks may be insufficiently elastic (Araujo et al., 2016). Nevertheless, caution is required to prevent that subjects simply enjoying the virtual environment show an even more inelastic response to incentives.

The main drawbacks of VR experiments are the costs of equipment and the required programming skills, although developments in the game industry might lead to cheaper devices and straightforward software, as well as improved specifications to minimize simulator sickness. At any rate, researchers should adhere to the conduct for the ethical use of VR, be aware of signs of simulator sickness and pay careful attention to the measurement of presence. Note that as technology advances, VR experiments have the potential to increase both in the realism and the control dimension. At the moment, the costs of starting a simple economic VR experiment are decreasing and the possibilities for testing and developing behavioral models are promising. Many university campuses around the globe already have a VR lab, for example in a psychology or computer science department. Collaborating with someone familiar with VR equipment and programming is an affordable way to conduct an economic experiment in VR. It might be the right time to consider using it.

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