Virtual Worlds from a Neuroscience Perspective: A Literature Review and Research Agenda

Thomas Fischer

Johannes Kepler University, Linz

Marshall Plan Scholarship Paper

Missouri University of Science and Technology, Rolla (MO)

March – August 2014

Table of Contents

TABLE OF CONTENTS I
LIST OF FIGURES I
1. ABSTRACT 1
2. INTRODUCTION 1
2.1. Research Potential 2
2.2. Research Goals 2
3. THEORETICAL FOUNDATION 3
3.1. Virtual Worlds 3
3.2. Neurophysiological tools 5
4. RESEARCH METHOD 7
5. REVIEW OF LITERATURE 11
5.1. Main Research Streams 13
5.2. Contributions of previous Research 16
6. RESEARCH AGENDA 20
7. CONCLUSION 28
REFERENCES 29

List of Figures

Figure 1: Virtual Worlds Population – Total accounts (millions) registered 1
Figure 2: Publications per Year 11
Figure 3: Neurophysiological Tools applied 12
Figure 4: Development of five most popular neurophysiological tools 13
Figure 5: Overall Contributions 18
Figure 6: Contributions to Research Streams 1 and 2 21
Figure 7: Contributions to Research Streams 3 and 4 21
Figure 8: Contributions to Research Streams 5 and 6 22
Figure 9: Contributions to Research Streams 7 and 8 23
Figure 10: Contributions to Research Stream 9 23
Figure 11: Neurophysiological Tools applied in Research Streams 1 and 2 24
Figure 12: Neurophysiological Tools applied in Research Streams 3 and 4 25
Figure 13: Neurophysiological Tools applied in Research Streams 5 and 6 26
Figure 14: Neurophysiological Tools applied in Research Streams 7 and 8 27
Figure 15: Neurophysiological Tools applied in Research Stream 9 27

1. Abstract

Virtual Worlds have experienced a long line of developments since the time of gaming arcades and are still growing in popularity. Science has acknowledged the potential of virtual worlds for research, especially in areas related to the human aspects of information systems (IS) use, yet new methods are needed to capture concepts under investigation in a more objective way. For this reason, the application of data collection methods which originated in neuroscience is getting more common in fields which have traditionally not been associated with neuroscience, such as IS research related to virtual worlds. Due to the complexity of neurophysiological tools and other risks related to their application (e.g., high costs or invasiveness in some cases) though, it has to be considered carefully whether a research endeavor is actually worth the application of such tools.

By conducting a literature review (N = 76), we therefore aimed on showing which neurophysiological tools have been utilized in virtual worlds research so far and which insights have been gained through their application. In addition, we propose a research agenda for virtual worlds research applying neurophysiological tools.

2. Introduction

In 2008, Messinger et al. (2008) reported on virtual world research as still being in its infancy due to scholars not yet being able to grasp the implications of virtual worlds' growing popularity, only starting to create appropriate research methodologies and acquiring or developing the necessary technologies to support their endeavors. Still, since 2008, many more people experienced virtual worlds and the worldwide virtual world "population" (i.e. the total number of accounts in virtual worlds) has grown to more than 2 billion, breaking the limit of 1 billion total accounts already in the third quarter of 2010 (Figure 1).

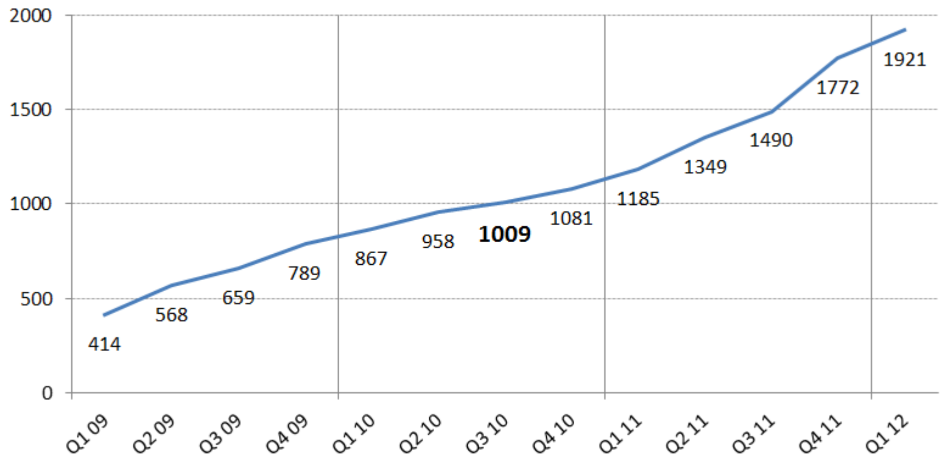


Figure 1: Virtual Worlds Population – Total accounts (millions) registered[1]

[1] http://www.kzero.co.uk/blog/virtual-world-registered-accounts-reach-1-7bn-q4-2011/ [17.05.2014].

2.1. Research Potential

Bainbridge (2007) pointed to the potential of virtual worlds for social, behavioral, economic and human-centered sciences, even allowing the conductance of experiments which have never been able before. Within time, various fields of research adopted this new environment, partially by reusing established methodologies and research designs like the *trust game*, a classic test of trust behavior (e.g. applied to human-avatar interaction by Riedl et al. 2014). At this point though, we have to argue that in the fields proposed by Bainbridge (2007), which are mostly centered on human-related phenomena, measurement of involved constructs can posit a challenge when relying solely on self-reports. As Dimoka et al. (2010) pointed out, participants might be unable or even unwilling to report in certain circumstances (e.g. when strong emotions are involved) and data gathered from self-reports can be further afflicted by biases like subjectivity, social desirability (i.e. participants might not provide their own opinion, but an opinion that they think is accepted by a wider public) and common methods (i.e. participants might guess or even know about the purpose of the study and then change their answers accordingly in order to create a result which they perceive as being preferable). Therefore, in order to gain more unbiased insights into related phenomena, Dimoka et al. (2012) proposed the use of neurophysiological tools, as these allow for more objective measurement. Measurement methods of this category include the collection of physiological data (e.g. involving changes in heart rate or skin conductance) as well as more complex methods focused on the imaging of brain activation (e.g. involving changes in membrane conductivity or the magnetic properties of blood circulating in the brain) (Riedl et al. 2010).
Still, utilizing neurophysiological measurements methods can inflict high costs (e.g. in the case of methods requiring expensive equipment like functional magnetic resonance imaging), data extraction and analysis can be labor-intensive and interpretation of results can be difficult, to cite some of the most commonly noted weaknesses of this category of research methods (Dimoka et al. 2012). Hence not every research question might be worth the effort and it is important to create an overview of the possible applications of neurophysiological tools in the area of virtual worlds research.

2.2. Research Goals

In order to grasp the extent of research which has already applied neurophysiological tools to topics related to virtual worlds, we will draw on a review of literature as research method of choice. In this context Cooper (1988) identified three possible **goals for a literature review**: Integration, Criticism or the Identification of Central Issues. *Integration* is focused on resolving conflicts within resembling streams of literature, *Criticism* is focused on the evaluation of existing research (e.g. against a formal criterion like rigor), and *Identification of Central Issues* focuses on the analysis of overall work done in a field. The main goal for this review will be the *Identification of Central Issues* as we will use existing literature to identify questions which have dominated research in this area in the past and then point out general topics which could benefit from further research in the future.

NeuroIS research (focused on virtual worlds) can derive **three main contributions** from this review, as we aim on supporting the first three steps in the typical progression of a NeuroIS study (Vom Brocke and Liang 2014):

1. The *identification of relevant research questions* will be facilitated by our concluding research agenda, which will be the result of an analysis of previous research. This analysis will focus on the concepts which have been under investigation before and how these areas of research can profit from additional contributions.
2. *Building a theoretical foundation* for selected research questions will be supported through our review of past research. Researchers can draw on this overview and identify the main contributions made so far more easily and thus facilitate the development of their research endeavor.
3. By *showing in which context neurophysiological tools have been utilized* as a means of data collection so far, researchers can more easily conclude how they might employ those same methods when *designing* their *experiments*.

3. Theoretical Foundation

In the following sections we will attempt to create an overview of both our introduced field of research (virtual worlds) and the introduced category of research methods (neurophysiological tools) as well as related terms which will enable us to conduct research and select relevant literature, as it constitutes the theoretical foundations we will use to precede throughout this thesis.

3.1. Virtual Worlds

Virtual worlds originated in the gaming sector about 35-40 years ago depending on which game is quoted as first original ancestor of today's virtual worlds. Messinger et al. (2008), for example, opt for arcade games in the early 1970's to be the first important step in the development towards virtual worlds. Bartle (2004) contradicts this view and suggests that MUD (multi-user domain), which he co-developed in 1978, to be the first real virtual world, thus focusing more narrowly on virtual worlds per se instead of the overall technological developments which led to their current state. Despite or perhaps even due to this long development in the area of virtual worlds, there is still a variety of different definitions and opinions on what constitutes a virtual world (Bell 2008). This circumstance makes it difficult to identify artefacts which can be classified as being "virtual worlds" and in the process complicates the identification of relevant articles. Therefore, we will have to first identify a proper definition for the concept of a *virtual world*, before going on.

The approaches presented in literature for this purpose tend to be quite diverse ranging from wide definitions like the one by Blascovich et al. (2002, p. 107 f), stating that: "*A virtual world is simply a superordinate model of a space (…) with smaller models (…) within it.*" to more narrow definitions like the one by Bainbridge (2007, p. 472), describing a virtual world as "*an electronic environment that visually mimics complex physical spaces, where people can interact with each other and with virtual objects, and where people are represented by animated characters.*" For our purpose, a more narrow definition is well suited as it allows for a clear distinction, although the approach by Bainbridge (2007) might already be too narrow for some parts (e.g. the sounds within a physical space could also be mimicked). Two almost congruent attempts to identify certain criteria that constitute a virtual world, instead of presenting a static definition, have been made by Bartle (2004) and Bell (2008) with four out of five criteria being listed by both:

1. **Persistent**: The world and its contents exist independent of them being used or not.
2. **Shared**: The world can be shared by a number of users which are able to interact with the world, but also with each other.
3. **Synchronous**: Interaction happens (almost) in real time.
4. **Representation**: Users interact with each other utilizing virtual characters (so called *Avatars*).

Bartle (2004) further adds the existence of *underlying, automated rules* in a virtual world and Bell (2008) adds *facilitation by networked computers*, which is supposed to distinguish virtual worlds from multiplayer games; criteria we will both treat as being optional. In order to assess whether the listed criteria are indeed appropriate to distinguish virtual worlds from related IS artefacts (like social networks and multiplayer video games), Bell (2008) applied them to two exemplary representatives of related IS artefacts, namely social networks and multiplayer video games:

Table 1: Virtual world criteria applied to popular IS artefacts

Example	Persistent	Shared	Synchronous	Representation
Facebook (exemplary social network)	✓	✓	✓	X
Mario Kart (exemplary multiplayer video game)	X	✓	✓	✓

In the case of *Facebook* (social network), all criteria are fulfilled except for *Representation* as there is no graphic character (Avatar) which a user can utilize to navigate through the virtual environment. *Mario Kart* also cannot be classified as virtual world when strictly applying the introduced criteria as it is a game that is played in sessions not offering a *persistent* world. Examples for virtual worlds as per the proposed classification (thus fulfilling all four criteria simultaneously) would be popular virtual environments like *SecondLife* (a virtual world mainly used for social interaction) or *World of Warcraft* (a virtual world mainly focused on gameplay).

As shown, the presented criteria can be used to effectively distinguish virtual worlds from related artefacts. Thus, these criteria will be adopted by us to define virtual worlds, though it still has to be confirmed whether they are too narrow for the selection of relevant literature or not (which will be discussed in Chapter 4).

3.2. Neurophysiological tools

In this section we will now introduce the category of measurement methods we are focusing on, namely *neurophysiological tools*. This type of tools includes methods which allow for the study of the human physiology and especially the brain, by measuring responses in humans, e.g. changes in heart rate or blood oxygenation in the brain (Dimoka et al. 2012; Riedl et al. 2010). In recent years, measurement methods of this category have become more affordable and more widely accessible and have thus seen adoption in various fields of research like the social sciences and also in IS (Dimoka et al. 2012). *NeuroIS* has in consequence been coined as a new term for the application of neurophysiological tools to IS (Dimoka et al. 2007), a term which we will adopt, due to our field of interest (i.e. virtual world research applying neurophysiological tools) being part of this new area of research.

Neurophysiological measurement methods can be a viable alternative to traditional methods of data collection like self-reports, due to them not being afflicted by the same weaknesses (i.e. aforementioned biases like subjectivity, social desirability, lacking ability or unwillingness to report on certain events). Still, instead of replacing self-reports with neurophysiological measurements, complementing various methods of data collection with each other can create an even bigger opportunity (e.g. by getting a more holistic picture of the phenomenon under investigation), especially when involved methods provide individual strengths and balance out each other's weaknesses (Dimoka et al. 2010).

An overview of the methods of data collection which are part of this category has already been provided by Riedl et al. (2010) as well as Dimoka et al. (2012) which we will both refer to at this point due to these reviews adding up to each other (i.e. Dimoka et al. 2012 feature fewer methods than Riedl et al. 2010, but cover these methods in more detail). Table 2 below shows the methods featured in both articles, a short introduction of their respective focus in measurement (i.e. what they measure and/or how they measure it) as well as an approximation of costs per hour (based on Dimoka et al. 2012, p. A8).

Table 2: An overview of neurophysiological measurement methods

	Focus of measurement	Approximate Costs (US $)
Psychophysiological Tools		
Eye Tracking	Eye gaze and movement	~ $ 100/hour
Skin Conductance Response (SCR)	Sweating of palms or feet	~ $ 25/hour
Facial Electromyography (fEMG)	Electric impulses caused by muscle fibers	~ $ 40/hour
Electrocardiogram (EKG)	Electrical activity of the heart on the skin	~ $ 50/hour
Brain Imaging Tools		
Functional Magnetic Resonance Imaging	Neural activity, by changes in blood flow	~ $ 200-500/hour
Positron Emission Tomography (PET)	Metabolic activity by radioactive isotopes	~ $ 200-500/hour
Electroencephalography (EEG)	Electrical brain activity on the scalp	~ $ 100-200/hour
Magnetoencephalography (MEG)	Changes in magnetic fields by brain activity	~ $ 200-400/hour

Riedl et al. (2010) proposed a number of additional data collection methods which can be used in NeuroIS, mostly applying a more direct approach to the analysis of the brain. The first way how researchers can study the functionality of the human brain is by analyzing the effects of **brain lesions**. Patients who suffered damage to their brain are studied and the observed effects of these lesions help to understand what kind of functionality the affected brain areas would usually administer. **Voxel-based Morphometry (VBM)** focuses on the composition of the brain by statistically analyzing the shares of grey and white matter it is consisting of. **Diffusion Tensor Imaging (DTI)** tracks the nerve fibres in the white matter of the human brain, analyzing the connection between different parts of the brain.

As it can be difficult to find a significant number of patients with brain lesions in the exact regions which are of interest for a specific research project, **Transcranial Magnetic Stimulation (TMS)** has been introduced as a possibility to temporary simulate brain lesions through electro-magnetic impulses. Nowadays this method is on the decline, as it has been found that this kind of stimulation can lead to permanent damage of the brain, thus being an invasive measurement method.

4. Research Method

So far we found that there is a wide variety of concepts related to virtual worlds and no commonly accepted definition for the concept of a “virtual world”. Also, we have shown that a number of neurophysiological tools have been proposed as being of high potential to IS, which led to NeuroIS being established as a new field of research. This variety in definitions and concepts as well as tools which we want to focus on requires a clear approach to the identification of relevant literature.

When conducting literature research, Webster and Watson (2002) therefore recommend to first consult the *leading journals* of the field, looking for those articles which are of value for the research purpose and then to utilize these articles for *backward search* (i.e. searching within the literature referenced in these articles) and *forward search* (i.e. searching within the literature citing the found articles, using services like Google Scholar or Thomson Reuters’ Web of Science). Although we wanted to adhere to these recommendations, the initial step (i.e. identifying the leading journals) already posed a certain challenge.

This challenge is due to our research interest involving the focus on a rather new approach to research in IS (i.e. NeuroIS), which is not yet confined to specialized venues (i.e. conferences and journals which are specifically focused on NeuroIS and attract the attention of a majority of researchers in the field) and at the same time being highly interdisciplinary in nature (e.g. virtual worlds have the potential to be applied in varying fields like entertainment, e-business, education, tele-working, research or the public sector, OECD 2011). Accordingly, Webster and Watson (2002) point to the requirement of including more than one set of journals in a review and to also look outside of the IS discipline in order to reach *completeness* when compiling the basis of relevant articles for a review. Still, achieving completeness does not necessitate the identification of all potentially relevant publications related to the field of interest, but to focus on those publications which are of critical value for the review. Therefore, completeness can already be achieved when research does not identify any more publications featuring new concepts (only studies which repeatedly investigate in the same areas). This overall notion is emphasized by Webster and Watson (2002, p. XVI), stating that: *“Of course, you will miss some articles. If these are critical to the review, however, they are likely to be identified by colleagues who read your paper either prior to or after your submission.”*

In order to identify relevant articles we will therefore opt for a slightly different approach than the one originally suggested by Webster and Watson. Our approach involves the utilization of **keywords** (Table 3) to conduct research within a **multidisciplinary literature database** which will constitute the main phase of our literature research as it allows us to simultaneously access a large number of potentially relevant journals. Publications identified in the course of this phase will then be used for **backward search** as well as **forward search**.

We have derived our set of keywords mainly from the *Theoretical Foundation* that has been established before, including terms mainly related to virtual worlds and neurophysiological tools. Thus, as visible in Table 3, these two categories of keywords comprise the biggest part of our total list of keywords. When analyzing literature in order to define virtual worlds we found that there is a number of terms which have been used for concepts that are similar to or even resembling virtual worlds. The most prominently cited concept in this context is arguably that of *virtual reality* (Bainbridge 2004; Bartle 2004). For the "virtual world terms" in our range of keywords we therefore also included *mixed reality* (Milgram and Kishino 1994), *multi-user domain* (Bartle 2004), *multi-user environment* (Nelson et al. 2005), *metaverse* (Davis et al. 2009), *synthetic world* (Castronova 2006) and virtual environment (Blascovich et al. 2002). Interestingly, the uniting feature of most definitions is their introduction of a virtual representation for the user which can basically take any form (Sherman and Craig 2003). The representation of actual humans in virtual worlds are commonly referred to as "Avatars" (or human-avatars), while simulated representations of non-human characters are called "agents" (or agent-avatars) (Blascovich et al. 2002; Guadagno et al. 2007). Thus, we also dedicated a section of keywords to the representations of users in virtual worlds, which is further supported by *Representation* being one of the defining characteristics of a virtual world.

Table 3: Keywords used for Literature Research

Virtual world terms	Neurophysiological tools	Additional terms
Metaverse	Brain (Activation / Lesions / Imaging / Morphology / Structure)	**Representation**
Mixed reality	Diffusion Tensor Imaging (DTI)	Agent
Multi-user domain	Electrocardiogram (ECG/EKG)	Avatar
Multi-user environment	Electro-dermal activity (EDA)	Assistant
Synthetic world	Electroencephalography (EEG)	Character
Virtual environment	Eye tracking	Face
Virtual reality	Facial Electromyography (fEMG)	Human(oid)
Virtual world	functional magnetic resonance imaging (fMRI)	Representation
	Magnetoencephalography (MEG)	**Related Concepts**
	Near infrared spectroscopy (NIRS)	Engagement
	Positron emission topography (PET)	Flow
	Psychophysiological Tools	Immersion
	(Galvanic) Skin (conductance / response) (SCR)	(Spatial / Social / Tele-) Presence
	Transcranial Magnetic Stimulation (TMS)	NeuroIS
	Voxel-based Morphometry (VBM)	Neuroscience

In order to conduct our literature research we had to choose an appropriate **database** (instead of initially identifying the main journals of the field) which, in its composition, reflected the nature of our research interest (combining several fields of research, as proposed by Bainbridge 2007), thus being interdisciplinary. Therefore, out of the licensed databases offered by the University of Linz[2], we have compared those covering several disciplines while at the same time including international (mainly English-speaking) publications. We selected Thomson Reuters' *Web of Science* based on the large number of journals indexed and the large base of conference proceedings which is included in the core collection (more than 150,000 conference proceedings[3]), due to conference proceedings being the second important source of peer-reviewed publications (next to journal articles) which we were interested in.

The research itself then involved the combination of each "virtual world" term with each neurophysiological tool, which also included the separate application of the abbreviation for each tool (in parentheses). As these combinations in many cases led to an overabundance of retrieved publications, we included further terms for these cases which would help us to focus on our specific research interest. These terms are mostly related to the *Representation* of the user within a virtual world as a distinguishing criterion, and we further added some *Related Concepts* which were also prominent during our initial research.

Due to the many different disciplines involved in our chosen field of research and the generic keywords utilized in the course of our first phase of research, we were confronted with a vast number of publications which, we figured, could at least be remotely relevant to our research interest (e.g. "Virtual World" + "Avatar" delivered more than 1,500 publications alone). In order to select those articles which are most relevant though, we decided to implement a **selection process**, which was composed of several steps, so we could handle this large number of publications.

First of all, we selected only *peer-reviewed* publications as recommended by Levy and Ellis (2006) in order to secure a minimum level of quality for the literature under investigation (implemented by refining for "Articles" and "Meetings" as Document Types in the Web of Science).

We were then interested in the actual contents of the found publications, where we had to decide whether a publication was relevant or not based on its *Title* and *Abstract* first before reviewing the full-text of a publication. We selected articles which indicated the combination of virtual worlds (i.e. which included one of our "virtual world terms") and at least one of the neurophysiological tools introduced.

Even though scanning over Title and Abstract of retrieved publications already gave us a good opportunity to identify the literature we needed to review, we still had to make sure that the publications we had selected thus far were actually related to virtual worlds research and applied

[2] http://rzblx10.uni-regensburg.de/dbinfo/dbliste.php?bib_id=ubli&colors=30&ocolors=0&lett=a [06.06.2014].

[3] http://thomsonreuters.com/web-of-science-core-collection/ [06.06.2014].

a general understanding of this area of research which at least resembled the one we had introduced when trying to define the concept of a "*virtual world*" for ourselves. When actually reviewing the publications we had accumulated at this point though, we found that there are **two main hindrances** which required us to reconsider the strict application of our classification criteria for selection purposes:

First of all, there is no commonly accepted definition for the concept of a virtual world, as well as a number of concepts which are closely related to virtual worlds as per our definition. Therefore, although we created our own definition of a virtual world for the sake of clearly distinguishing the concept from related terms and concepts, only a small fraction of research might have applied this same understanding, although nonetheless contributing to the research of virtual worlds (as per each specific definition).

Second, it was expected that most studies identified are actually laboratory studies, due to neurophysiological tools in many cases not being applicable to research settings in the field (e.g. the availability of fMRI is often limited to hospitals) and actual virtual worlds including so many potentially contradicting variables (e.g. events, social interactions and further possible developments and actions which cannot be fully controlled) that the thrive for more external validity would compromise the internal validity of conducted studies. It was therefore unsurprising, that we found only one study which utilized an actual virtual world, as per our definition, as research environment (i.e. Lim and Reeves 2010).

Therefore, a strict application of the criteria which we adopted as being the distinguishing traits of a virtual world would have led to an overly limited review of virtual worlds research. Therefore we included all studies which utilized a graphical virtual environment (i.e. virtual worlds, virtual reality simulations, but also video games) in our review as we argue that findings of these studies could easily be translated to other related applications (e.g. findings related to the influence of violence in video games can also be applicable to violent scenarios in a virtual reality application or a virtual social world). Further, as the concept of *Representation* of a user in a virtual world is the most widely mentioned distinguishing criterion of a virtual world, we additionally included studies which did not involve the use of an actual virtual environment, but contributed to virtual worlds research nonetheless by focusing on research in this specific field.

Altogether we created a wider approach to one of the two major areas we wanted to see combined (i.e. the understanding of virtual worlds), but still adhered to the application of neurophysiological tools as selection criterion. Based on this second criterion in our final selection we excluded studies from our review which either not used neurophysiological tools at all or did not use them as a means of scientific data collection (e.g. as an input channel for a brain-computer interface).

5. Review of Literature

Through our selection process we were able to identify a total of 76 studies which are fulfilling the presented criteria and are therefore relevant for the sake of our research interest. Although the development of virtual worlds already started at the end of the 1970s, there are no studies included in this review which were published before the year 2001. Since that year, the number of annual publications (Figure 2Figure 2: Publications per Year) saw an overall increase, with some ups and downs especially soon after the start of two of the most popular virtual worlds Second Life (2003) and World of Warcraft (2004). Thereafter, from 2008 onwards, we can see a steady number of annual publications with a slight upward progression except for 2013 and 2014 (for 2014 obviously because it is the current, unfinished year and for 2013 presumably because not all publications of this year have yet been indexed). It can also be stated that the overall interest in these studies is high, with no publication before 2011 not being cited at least once at this point. The five most important venues (by number of publications) for studies addressing virtual worlds from a neuroscientific perspective at the moment are *Cyberpsychology, Behavior and Social Networking* (Impact Factor as per SCImago of 2.63/ 8 publications included); *Presence: Teleoperators and Virtual Environments* (1.62/ 6); P*sychophysiology* (3.47/ 5); *PLoS One* (3.68/ 4); and *Frontiers in Human Neuroscience* (4.2/ 3). The respective impact factors of these journals highlight the overall quality of publications in this field and the potential of research endeavors combining virtual worlds research and neurophysiological tools to culminate in high-value publications.

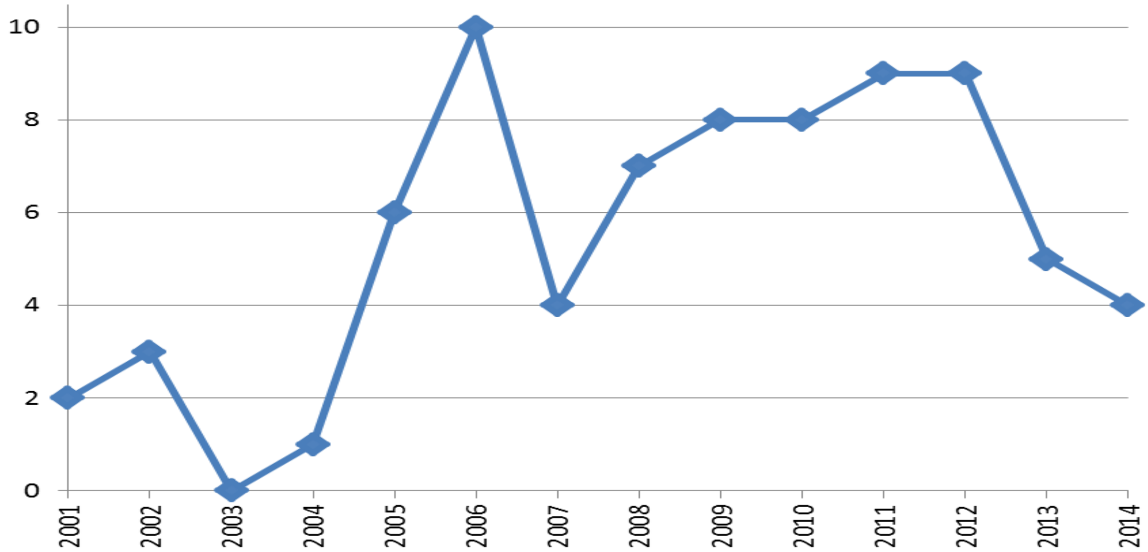


Figure 2: Publications per Year

Next to the overall development of publications in the field there are also interesting developments when it comes to the **neurophysiological tools** that have been used in the various research endeavours included. Figure 3 shows all neurophysiological tools which have been utilized at least more than once in the studies reviewed, with blue data sets visualizing tools we had already introduced and red data sets visualizing those tools which were used as well, but had not been introduced before.

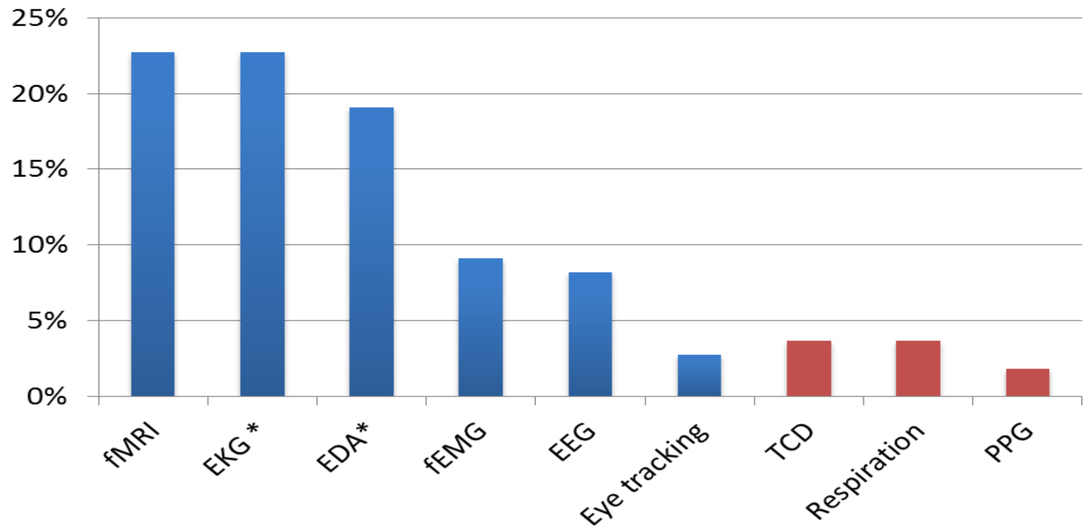


Figure 3: Neurophysiological Tools applied

In this overview we can see that fMRI as well as the measurement of cardiovascular activity (we have included EKG as well as other measurements of heart activity in this figure) are most commonly applied in virtual worlds research so far, closely followed by the measurement of electrodermal activity (we have included skin conductance response as well as other skin-related measures like skin temperature in this figure). Surprisingly, eyetracking saw only marginal application and about half of the tools we had introduced were only applied once or not at all throughout the studies we have reviewed (i.e., once: PET, NIRS, VBM, TMS; not applied: MEG, DTI, study of brain lesions).

Interestingly there are also a number of neurophysiological tools we had not included before, which still saw a limited number of applications: **TCD** (transcranial doppler sonography or transcranial doppler monitoring) is an alternative method to measure brain activity by tracking the blood flow in cerebral arteries based on changes in blood flow velocity (e.g. Alcañiz et al. 2009), other studies measured a wide number of psychophysiological responses and also included **respiration** (e.g. Moore et al. 2002; Johnson et al. 2011) and/or **PPG** (photophletysmogram) which is an alternative approach to measuring cardiac activity by analyzing the changes in light absorption of the skin when blood is pumped through, e.g. at the finger tips (e.g. Kim et al. 2005; Persky and Blascovich 2008). Further psychophysiological measurement methods which have been applied by Kim et al. (2005) in order to track the creation of cybersickness are **EOG** (Electrooculogram) which is an alternative technique for measuring eye movement by placing pairs of electrodes next to the eye and **EGG** (Electrogastrogram) which is a method for analyzing the electrical activity in the area of the stomach that lead to its contractions. One study even included biological measurements (which we did not feature in our set of tools as well), i.e. Kotlyar et al. (2008) measured the excretion of certain hormones in blood samples taken from participants.

In addition to these neurophysiological tools which we have not credited before, there have been visible changes when it comes to the overall use of the different data collection methods included and especially related to fMRI. Due to the rather small number of publications per year, instead of analyzing the share each neurophysiological tool accounted for in annual figures, we looked at the chronologically first half of the time span under review (i.e. 2001-2007) versus the second half of the time span under review (2008-2014). The comparison (Figure 4) revealed that psychophysiological tools (EKG, EDA and fEMG) were by far the most important means of measurement in the first half of the time span under review with measurements of cardiovascular and electro-dermal activity accounting for more than half of the tools which have been utilized in the studies of this time period. The most frequently applied brain imaging tool, fMRI, accounted for only 14% of the methods used in this period of time. This picture changed quite tremendously when we look at studies which have been published between 2008 and 2014. Here, fMRI is by far the most prominent tool used and brain imaging tools (fMRI and EEG) increased their total share from 23% to 36%. Still, psychophysiological tools remain important and their three most important representatives (EKG, EDA, fEMG) are present in around half of the instances where neurophysiological tools have been used as means of data collection. A final important observation which can be made here, is the total share which the five most important tools occupy in the reviewed base of studies. Of a total of 11 tools (excluding biological measurements based on hormone analysis), only five (either alone or in combination) have been used in more than 80% of the cases.

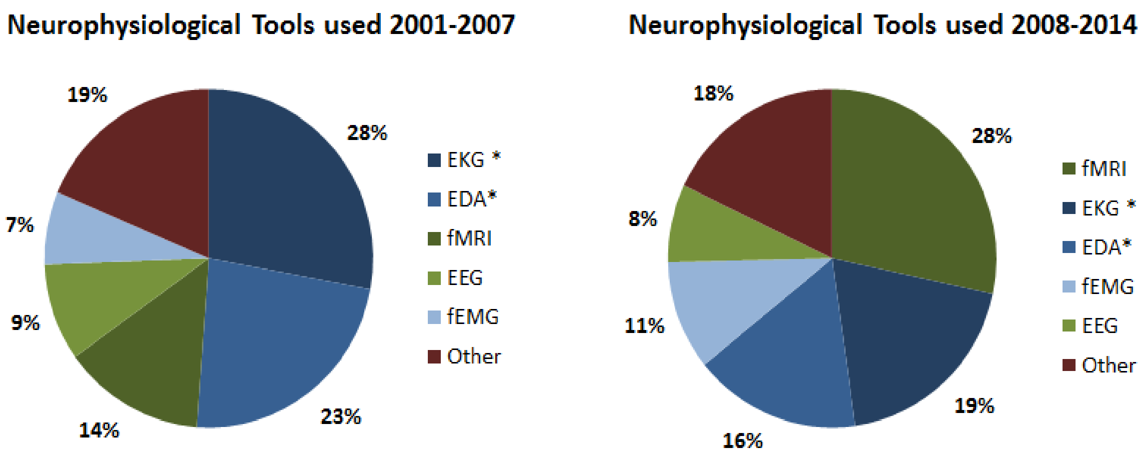


Figure 4: Development of five most popular neurophysiological tools

5.1. Main Research Streams

In order to show which concepts have been analyzed in previous studies we combined similar studies into a total of nine research streams. The creation of these research streams was based on common variables which were involved and the topics these studies were mainly interested in (as presented in abstract, introduction and/or the conclusion of these studies). For all studies it was decided which stream they mostly contributed to (based on included hypotheses and contributions), which led to a number of studies not only being included in one of these categories, but in several of them. Subsequent to the categorization of reviewed studies into these research streams, we attempted to synthesize the major findings which have been generated through application of neurophysiological tools.

Research Stream 1: General Effects of Exposure to Virtual Worlds (12 Studies)

This research stream mainly comprises studies which focus on showing which effects the exposure to a virtual experience (e.g. a virtual environment setting or a video game) has on the human physiology or brain processes and studies which try to investigate how this experience of virtuality can be captured. In this category we included mainly research that showed how the modulation of certain aspects of a virtual environment changes the reaction to these environments and research which more generally tried to establish a baseline for diverse applications of virtual worlds. A significant number of studies in this group can also be found in research stream 6 "Anxiety in Virtual Worlds" as these studies tried to establish a baseline for applications like virtual exposure therapy and in this wake also showed how a control group (e.g. a group of people which are not anxious or phobic) generally reacted to a virtual setting.

Research Stream 2: Technological Aspects of Virtuality Exposure (7 Studies)

Studies in this research stream focused on how the variation of technological aspects of a virtual environment can change the bodily reactions users have when being exposed to it. In many cases this variation altered the level of immersion of the virtual environment (i.e. how much the user's senses are involved in the virtual experience, Rey et al. 2010) and therefore aimed on creating a more engaging experience for participants. We did not only include studies in this category which altered the level of immersion, but also studies which focused on changes in realism of elements in the virtual environment which might have an impact on the virtual experience.

Some studies in this category are also found in research stream 4 "Effects and Aspects of Presence in Virtual Worlds" as it has been theorized that alterations in immersion could potentially change the level of presence that users experience in virtual environments.

Research Stream 3: Virtuality – Reality Differences (9 Studies)

As indicated by the title of this research stream, studies in this category focus on comparing the reactions users show when faced with real and virtual stimuli. These stimuli are in most cases related to perception (e.g. virtual representations of real objects like arms or faces) or behavior (e.g. simulated driving compared to real driving). Accordingly studies which compared reactions to real and virtual stimuli were included in this research stream.

As it is of course essential for research in this category to measure the general effects of exposure to a virtual environment in order to create a comparison with reactions to real stimuli, we basically could have included all studies of this category in research stream 1 "General Effects of Exposure to Virtual Worlds". Still, due to the explicit focus on both the real and virtual variations of a stimulus and their comparative analysis, this category was included, though one has to keep in mind that there is a strong relation to studies in research stream 1.

Research Stream 4: Effects and Aspects of Presence in Virtual Worlds (17 Studies)

The predominant research stream in this compilation is composed of studies which focus on the concept of "*presence*" in virtual worlds, defined as the "*sense of being there*" (e.g. Meehan et al. 2002, p. 645) which basically means that users in the context of virtual worlds feel like they are, to some degree, actually inside a virtual environment. We generally included all studies which mainly focused on the concept of presence in this category, which entails research on the bodily reactions associated with presence, but also research on the prerequisites for the onset of presence or its relation to other concepts like anxiety.

Research Stream 5: Aspects of Social Interaction in Virtual Worlds (16 Studies)

In this research stream we compiled all studies which are focused on the interaction of the user with other humans or representations of humans in virtual worlds. This category therefore includes a wide area of different research endeavors focused on: e.g., interaction types (e.g. cooperation vs competition), gaze direction, facial expressions or proxemics and how variations of different elements involved in social interaction can influence certain outcomes (e.g. whether trust discrimination is influenced by the type of interaction partner, Riedl et al. 2014). Studies which required participants to interact with humans or representatives of humans were thus included in this research stream.

Due to this wide area of research included in this category, many studies listed here can also be found in other categories like 7 "Representation in Virtual Worlds" or 8 "Agency/ Self-Involvement".

Research Stream 6: Anxiety in Virtual Worlds (9 Studies)

Concepts related to stress in virtual world settings are also a popular topic in virtual worlds research. Therefore we included research related to sources of stress, mainly anxiety, in this research stream. Studies in this group are interested in the simulation of certain real world situations which might induce stressful outcomes related to anxiety or phobias, which can then be used for interventions and treatments of these mental problems. Also, a number of studies were interested in the sickness-inducing quality of virtual environments, focusing on Cybersickness and how this downside of virtuality exposure can be qualified and predicted.

As mentioned in research stream 1 "General Effects of Exposure to Virtual Worlds" many of the studies included in this category also showed how a control group reacted to a virtual environment, which makes these studies therefore interesting for both research streams.

Research Stream 7: Representation in Virtual Worlds (11 Studies)

In this category we have combined research that focused on the representations of humans in virtual worlds. Research related to representation in virtual worlds mainly focused on the effect of realism of virtual humans on bodily reactions and the potential of using Avatars instead of traditional stimuli (e.g. using Avatars in studies of facial expressions or using Avatars for communication instead of actual video chat). We have included all studies in this category which used representations of humans and varied certain aspects of these Avatars/Agents (depending on whether they have been controlled by a human or the computer), in order to create a better understanding of the design of such representations and/or their general use in virtual settings.

Research in this area is highly related to research stream 5 “Aspects of Social Interaction in Virtual Worlds” as it is often a side goal of studies focused on social interaction to additionally show that Avatars can be used as stimuli instead of real humans.

Research Stream 8: Agency/ Self-involvement (12 Studies)

Many studies focused on the different effects elicited by scenarios where users actively participate in a virtual environment compared to those situations where they only observe actions (a concept which has been given many names like interactivity, ownership, navigation freedom, which we will commonly refer to as “Self-Involvement”) and the perceptual differences which occur when a user is interacting with an Avatar (i.e. a human-controlled virtual entity) rather than with an Agent (i.e. a computer-controller virtual entity) (i.e. the variation of “Agency” in an interactional partner). Most studies in this category investigated these differences by utilizing video games and e.g., differed between active gameplay and showing automated movements or between playing with/against another human or computer. Unsurprisingly, an important part of these studies also contributed to the knowledge on processes of social interaction and can therefore also be found in research stream E) “Aspects of Social Interaction in Virtual Worlds”.

Research Stream 9: Effects of virtual Violence Exposure (8 Studies)

A final important research stream focused on violence in virtual environments, mainly games, and the effects of violent content (e.g. short-term exposure, but also chronic exposure) on bodily reactions and more explicit outcomes like aggressive behavior. The biggest part of these studies focused on potential desensitization to violence after being exposed to virtual violence on a regular basis, a topic which received considerable attention in media in the last years due to the assumption that violent video game exposure might be involved in the formation of aggressive behaviors.

5.2. Contributions of previous Research

At this point we will now indicate which types of contributions have been made by previous research and which role neurophysiological tools have played in this context. For this purpose, we adopted the seven opportunities of cognitive neuroscience for information systems research proposed by Dimoka et al. (2010) in order to classify the contributions which have already been made in previous research. To be able to use these seven opportunities as classification system in this context, we had to make some adaptations as Dimoka et al. (2010) focused on IS research and brain imaging tools. Therefore, we generalized these seven opportunities to include not only brain imaging tools, but all neurophysiological tools which have been introduced up to this point and we did not only focus on IS related constructs or concepts, but on contributions independent of their field of origin, as we have seen that many fields of research aside from IS did investigate the characteristics and effects of virtual worlds thus far.

The results of this generalization and the original description of each opportunity as per Dimoka et al. (2010) can then be found in Table 4 below.

Table 4: Classification of Opportunities

Dimoka et al. 2010 (p. 2)	Generalized Opportunities
Localize the various brain areas associated with IS constructs (neural correlates of IS constructs) and link them to the cognitive neuroscience literature to map IS constructs into specific brain areas, learn about the functionality of these brain areas, and better understand the nature and dimensionality of IS constructs.	(1) Identify **responses associated with constructs**
Capture hidden (automatic or unconscious) mental processes (e.g., habits, ethics, deep emotions) that are difficult or even impossible to measure with existing measurement methods and tools.	(2) Capture **hidden** mental **processes**
Complement existing sources of data with brain imaging data that can provide objective responses that are not subject to measurement biases (e.g., subjectivity bias, social desirability bias, common method bias).	(3) **Complement** existing sources of **data**
Identify antecedents of IS constructs by examining how brain areas are activated in response to IT stimuli (e.g., designs, systems, websites) that intend to enhance certain outcomes (use behavior, productivity).	(4) Identify **antecedents** of constructs
Test consequences of IS constructs by showing whether, how, and why brain activation that is associated with certain IS constructs can predict certain behaviors (e.g., system use, online purchasing).	(5) Identify (behavioral) **consequences** of constructs

Infer causal relationships among IS constructs by examining the temporal order of brain activations (timing of brain activity) stimulated by a common IT stimulus that activates two or more IS constructs.	(6) Infer **causal relationships**
Challenge IS assumptions by identifying differences between existing IS relationships and the brain's underlying functionality, thus helping to build IS theories that correspond to the brain's functionality.	(7) **Challenge** existing **assumptions**

Based on the description of these opportunities, we analyzed the literature in the course of our review and attempted to classify the varying studies to show which kind of contributions they have made. Figure 5 is showing the overall result of this classification, indicating the percentage of studies which made a contribution to each one of these classes of opportunities.

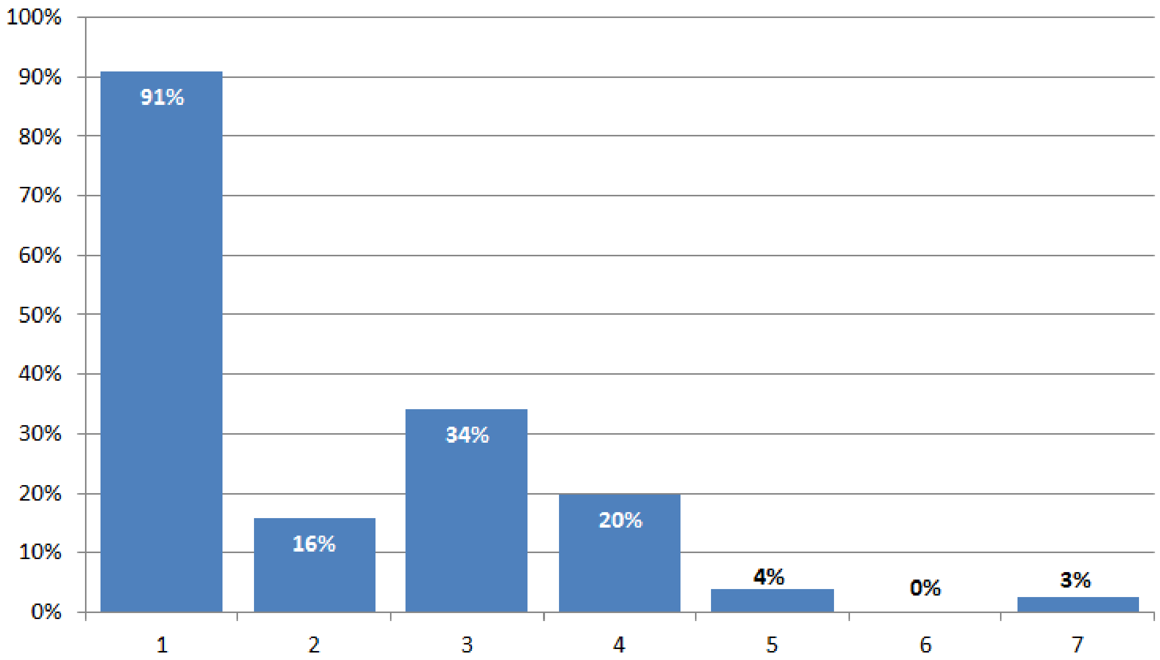


Figure 5: Overall Contributions

As to expect from a rather new field of research, many studies contributed to virtual worlds research by exploring which types of responses are characteristic for certain constructs (i.e. Opportunity 1). We here included all studies which aimed on identifying responses associated with involved variables, even if this contribution was only a first step towards more specific insights (e.g. to create a baseline and then vary certain aspects of the stimulus). A small portion of studies then, focused on capturing hidden processes which participants were not aware of (Opportunity 2), e.g. desensitization in response to virtual violence exposure or reflections about an interactional partner's intentions. The share of studies which tried to capture these types of processes might actually be bigger, as we based our classification in the majority of cases on the main contributions that have been laid out in the corresponding publications. It is therefore possible, that contributions of this type have been made more frequently, but due to the difficulty in validating the existence of found mental processes, have not received as much attention. In one third of the reviewed studies neurophysiological tools, especially psychophysiological tools as we see later on, have been used as further means of data collection in addition to self-reports (Opportunity 3). For Opportunity 4, we included all studies which utilized neurophysiological tools to show the antecedents of certain constructs.

These contributions have also been made quite frequently, mostly in the wake of investigating the overall nature and dimensionality of constructs (i.e. Opportunity 1). The consequences of constructs (i.e. Opportunity 5) have been limited to behavior, as suggested by Dimoka et al. (2010). Therefore, most studies which showed the consequences of constructs on physiological or brain activity have been included in Opportunity 1. Still, so far there is only a marginal portion of research which actually focused on showing that constructs related to virtual worlds change observable outcomes, a circumstance which was quite surprising and indicates the need for further research based on previous findings. For opportunities 6 ("Infer causal relationships") and 7 ("Challenge Assumptions") we did not expect to find a big number of contributions as these are arguably the most challenging classes of contributions which can be made, due to the difficulty of inferring causal relationships in comparison to identifying correlations and the potential reluctance to argue against existing paradigms. Yet, a number of studies, in part successfully, attempted to challenge existing assumptions, but we found no study that tried to infer causal relationships using neurophysiological tools in the way proposed by Dimoka et al. (2010).

One has to acknowledge at this point that it mostly depends on the abilities and limitations of each measurement method in which way they can be used to collect relevant data. Still, for each tool there are some clear tendencies which can be useful in order to assess which types of tools might be especially useful for each type of contribution. As shown further above, Opportunity 1 is most prevalent amongst all studies in this portion of virtual worlds research. For most tools listed, their application was aimed on creating a contribution of this type in more than 50% of the cases, but especially brain imaging tools (e.g. fMRI and EEG) were over-proportionally often used for this end. Capturing hidden processes in comparison (Opportunity 2) often required a different set of tools, with the exception of fMRI which remains at its place of the most popular neurophysiological tool as well in this group. Additionally, the measurement of facial muscular activity via fEMG was often used to assess valence, i.e. one of the two main dimensions of emotions which is a value for emotional loading (i.e. more positive or more negative) next to arousal which is indicating the strength of an emotion (e.g. Ravaja et al. 2006a; Ravaja et al. 2006b; Kindness et al. 2013). Measuring the extent of emotional loading therefore seems to be an excellent venue of application for fEMG, presumably due to the before indicated biases which are involved when participants are required to report on subjective matters of this kind. When it comes to the collection of data in addition to existing sources of data like self-reports (Opportunity 3), psychophysiological tools are most often used. From the reviewed studies we were able to observe that heart-related and skin-related measures were mostly used as indicators for arousal and facial muscular activity was used as an indicator for valence.

The only type of opportunity which shows almost equal application of brain imaging tools and psychophysiological tools is Opportunity 4, which includes studies aimed on identifying the antecedents of the constructs under investigation. Still, so far only four tools (i.e. fMRI, EEG as well as measurements of cardiovascular and electro-dermal activity) have been applied in this category which also indicates potential for further research.

6. Research Agenda

Based upon the findings we have presented so far we will propose a research agenda for the future application of neurophysiological tools to virtual worlds research which will include:

- Contributions made and still needed per research stream
- Neurophysiological tools applied and not applied per research stream

From what we have learned so far in relation to already made **contributions**, most studies focused on investigating the nature and dimensionality of certain constructs (i.e. Opportunity 1). In order to know more specifically which contributions are still needed, we repeated this analysis for all of our nine research streams.

The contributions made to the first two research streams are depicted in Figure 6 below, though we will only discuss the second research stream ("Technological Aspects of Virtuality Exposure") as the first research stream is basically including those studies which did not explicitly fit into one of the other research streams, but many of the studies included in other streams could also be easily assigned to this first research stream. Altogether though, research stream 1 is reflecting the picture we have drawn before for the overall contributions made.

With regards to the "*Technological Aspects of Virtuality Exposure*", we can see that there have not been any studies so far which dealt with hidden mental processes and interestingly, like for research stream A, as many studies focused on complementing existing data (Opportunity 3) as on finding antecedents of constructs (Opportunity 4). Still, aside from necessary contributions related to Opportunity 2, we can also see that there is only a small portion of studies which focused on identifying behavioral consequences of technological aspects (Opportunity 5), which might be one of the most worthwhile endeavors in the context of this stream (e.g. finding out whether different levels of immersion can influence technology acceptance or impact buying behavior).

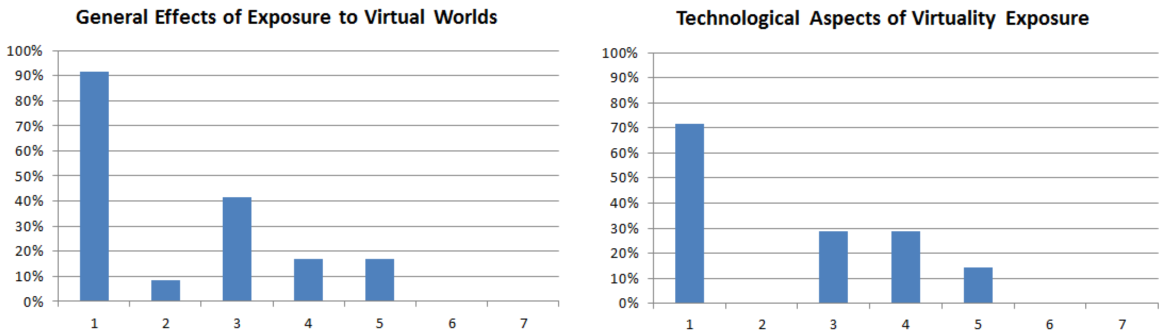


Figure 6: Contributions to Research Streams 1 and 2

For research streams 3 and 4 we can also quite easily identify major gaps which need to be closed by further research as presented in Figure 7. In the case of studies focusing on "*Virtuality – Reality Differences*" contributions have almost exclusive been made to show the nature of virtuality exposure (i.e. Opportunity 1). It would still be interesting to see how found differences or commonalities in this context can be explained and by which specific factors they are evoked (i.e. antecedents, Opportunity 4) and which consequences these characteristics of virtuality as compared to reality have on specific behaviors (e.g. development of trust and/or buying decisions), i.e. Opportunity 5. Research into *Presence* has clearly seen more diverse contributions, but is also lacking studies into the consequences of different levels of Presence, aside from changes in brain activations or psychophysiological responses (i.e. Opportunity 5).

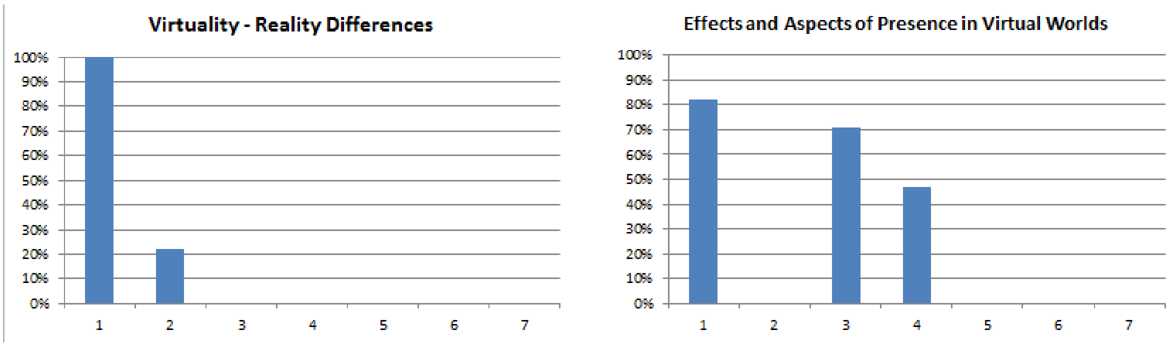


Figure 7: Contributions to Research Streams 3 and 4

Social Interaction (Figure 8) as expected from a research stream with a wide variety of different topics, offers a more balanced set of contributions. We can see that all of the studies in this category contributed to one of the first three Opportunities, though this category also lacks investigations into antecedents and consequences or causal relationships of involved variables and only one study focused on challenging existing assumptions (Soussignan et al. 2013). Due to the diversity of included topics it is also not surprising that no studies were yet interested in the antecedents of constructs, but we think that especially this type of contribution could be a resourceful field of research in the context of social interaction e.g. when it comes to identifying success factors of interactions aiming to establish certain states like enhanced levels of trust.

Anxiety (Figure 8) related research shows quite a different picture, not as much focusing on the identification of hidden mental processes. This "gap" is quite reasonable as in most cases emotional reactions (mainly arousal) are measured by means of neurophysiological tools and self-reports in combination (an indicator for the importance of Opportunity 3 in this research stream) with self-reports in many cases still being able to explain more variation in measured variables. As many studies in this research stream tried to establish a baseline of some sort (e.g. for virtual exposure therapy), it is not surprising that Opportunity 1 is also most prominent in this research stream, though a small portion of studies also focused on finding antecedents or consequences of stress-related concepts like anxiety or phobias in virtual worlds. Still, this research stream could also benefit from research which is utilizing previous findings on the nature and dimensionality of included constructs and create insights into their relation with other concepts (e.g. anxiety and presence, as done by Felnhofer et al. 2014).

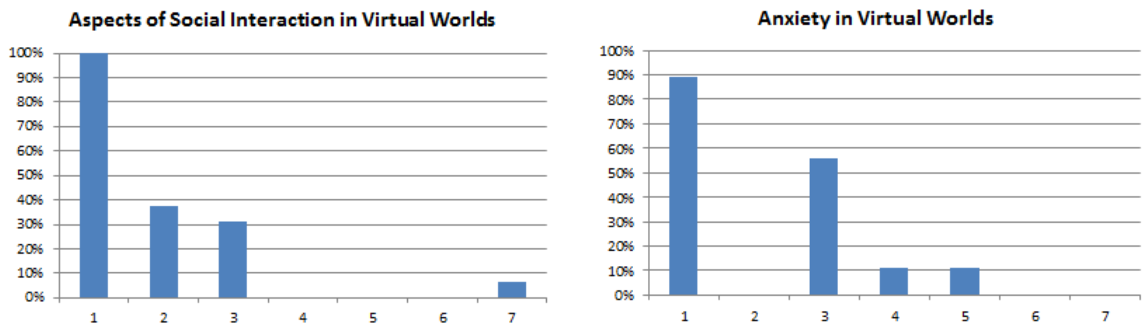


Figure 8: Contributions to Research Streams 5 and 6

The studies which focused on "*Representation in Virtual Worlds*" and "*Agency / Self-Involvement*" (Figure 9) did contribute in a quite similar way. Next to the nature and dimensionality of constructs, especially the antecedents of involved constructs were studied. In the case of representations, research mainly aimed identifying those factors which could facilitate a successful imitation of a real human being by a virtual character. In the case of studies involving agency and self-involvement, these factors itself were tested as potential antecedents for other constructs mostly related to Social Interaction.

We have not seen any contributions to Opportunities 2 and 5 in these research streams yet, though it would certainly be interesting to know which consequences the human-likeness of virtual agents or the interactivity of virtual worlds has on real-life behaviors.

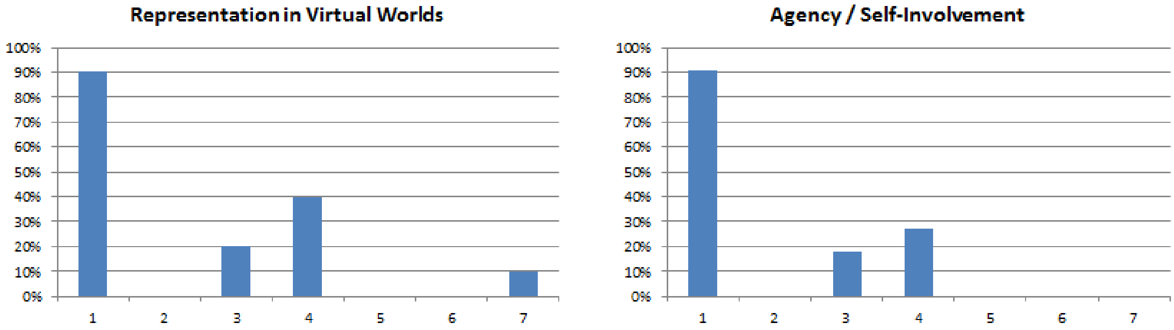


Figure 9: Contributions to Research Streams 7 and 8

For the "*Effects of virtual Violence Exposure*" (Figure 10) we can see that, almost like for Social Interaction, contributions have been made so far only to the first three Opportunities. The importance of capturing hidden mental processes can be explained by the popularity of showing desensitization effects to violence exposure in virtual worlds and how they change certain bodily reactions to virtual stimuli. As there are different findings for actual desensitization and similar types of settings (i.e. game play, then processing of scenes or images) throughout the studies up to this point it also not yet clear what specifically caused the found effects, i.e. there are no findings on its antecedents. For the consequences of virtual violence exposure none of the studies have tried to link it to real world behaviors, but Persky and Blascovich (2008) have already tried to gain insights regarding differences in aggressive behaviors within virtual worlds caused by desensitization to violence. Contributions to both of these Opportunities (antecedents and consequences) are highly needed in order to actually define what specific characteristics of violent games lead to desensitization and which effects desensitization to violence has on real-world behaviors.

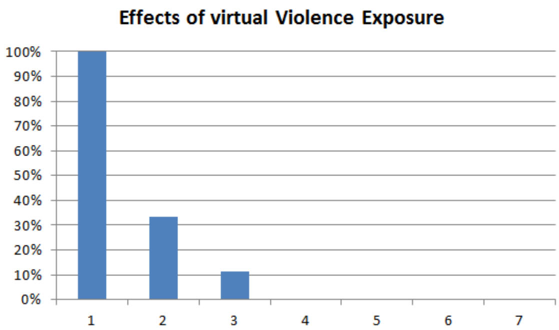
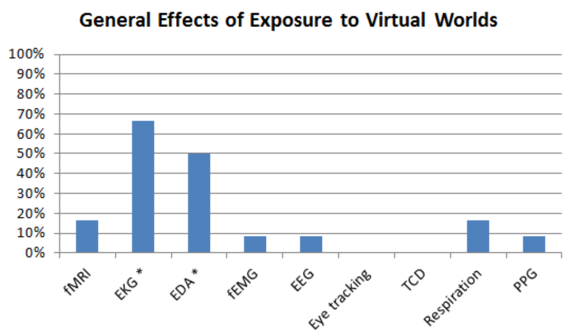


Figure 10: Contributions to Research Stream 9

When looking at the **neurophysiological tools** applied per research stream we can see that they draw an even more diverse picture than what we have seen so far from the contributions made. Here, based on previous applications, we can identify whether there are still tools that have not been applied to a certain type of topic and might still need to be tested for their applicability, but we can also learn whether certain types of data (e.g. brain activation) have not been captured in relation to a research stream yet and also potentially identify measurement methods which have become prevalent in a field (e.g. *Anxiety*). As done before, we will discuss these matters per research stream, showing which of those tools that have been utilized at least more than in one study have been applied as part of a research stream and how important they have been so far (i.e. how the big the share of studies is which used the specific neurophysiological tool).

The first two research streams "*General Effects of Exposure to Virtual Worlds*" and "*Technological Aspects of Virtuality Exposure*" (Figure 11) show a quite balanced use of different neurophysiological tools, though in the case of studies investigating the effects of virtual worlds in a general sense, psychophysiological tools and especially measurements related to cardiovascular and electro-dermal activity are most popular. It is not surprising that fEMG has not yet been used in the context of technological aspects, as different levels of immersion have often been simulated by utilizing a virtual reality setting which involved devices like head-mounted displays. As these displays need to cover areas of the face, mostly the eyes, where sensors would be attached for the measurement of facial muscular activity, it is complicated to combine such tools in these settings, the same being relevant for eyetracking. It is interesting though that none of the studies we assigned to research stream 1 utilized eyetracking yet as we would expect that this research stream focused on showing general effects of virtuality exposure along the line of as many different measures as possible. Both research streams also show a rather limited application of brain-imaging tools, the exact opposite of what we presented early in the previous chapter when we showed which tools have overall been most frequently applied. Therefore we would expect to see more applications of brain-imaging tools, most likely fMRI, in studies which want to contribute to either of these two groups.



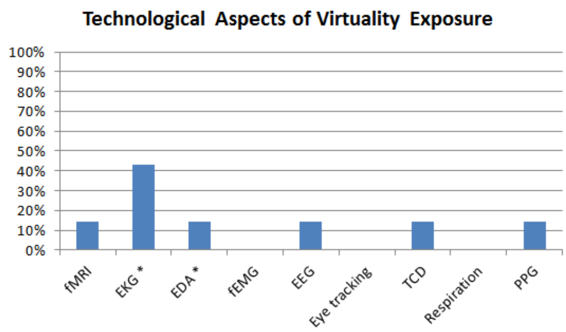


Figure 11: Neurophysiological Tools applied in Research Streams 1 and 2

Studies which mainly tried to identify "Virtuality – Reality Differences" (Figure 12) were particularly interested in underlying brain activations and therefore almost exclusively applied brain-imaging tools (i.e. fMRI and EEG). Still, the picture of applied tools in this field might be more diverse if one also counts in those studies which did not directly compare between virtuality and reality, but instead used stimuli which were intended for a similar purpose (e.g. studies focusing on Agency, when reactions to human and computer competitors have been compared or comparisons of responses to facial expressions of pictures of humans and virtual humans). Yet, it is nonetheless interesting to recognize that psychophysiological tools have so far only been marginally used in research which explicitly focused on the comparison of responses to virtual scenarios and their real world counterparts. Hence, we think that this gap should be closed utilizing tools of this group in order to measure changes especially in electro-dermal activity or oculesic behavior. For the biggest research stream in our review, i.e. those studies which aimed on investigating the "*Effects and Aspects of Presence in Virtual Worlds*" (Figure 12), we can see that almost every of the main neurophysiological tools presented has already been applied to investigate in which circumstances Presence occurs and to find an objective measure for this concept. In this area it is therefore especially difficult to say which types of tools might be applied more often in the future or which tools might have to be additionally applied in order to test their predictive value. As Felnhofer et al. (2014) had quite recently shown that measurements of cardiovascular activity might not have the ability to predict varying levels of Presence as indicated in a number of studies before (e.g. Meehan et al. 2005), we would guess that instead of applying psychophysiological tools, future studies will more often directly identify the neuronal activations related to the feeling of Presence. As we will discuss further below this also creates the opportunity of resolving contradicting findings which have been made so far.

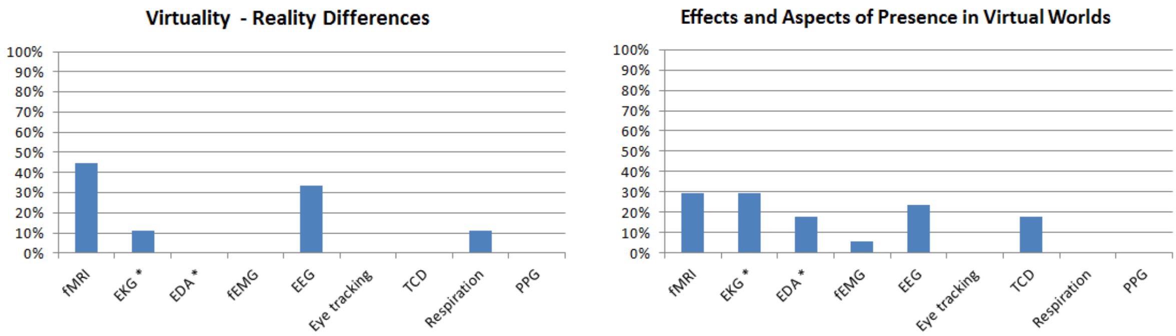


Figure 12: Neurophysiological Tools applied in Research Streams 3 and 4

The wide area of studies interested in the various aspects of *Social Interaction* (Figure 13) applied a similar diverse range of neurophysiological tools. Specifically, psychophysiological tools used to measure the two dimensions of emotion (i.e. EKG and EDA for arousal and fEMG for affect) were most popular in this research stream with brain-imaging tools only being applied in a rather small portion of the included studies.

It is quite unexpected that those studies which applied brain-imaging tools directly applied fMRI instead of first utilizing EEG or TCD to see whether there are overall changes in brain activation in response to different stimuli. Perhaps additional applications of these tools can help to gather further data which could be connected to the changes in psychophysiological reactions that have already been identified. Further, measuring changes in respiration would be a suitable addition to the so far utilized tools at it has been successfully applied in other areas in the past like in relation to *Anxiety* in order to track changes in arousal. Out of the nine research streams, "*Anxiety in Virtual Worlds*" (Figure 13) is the only one where we can see a clear preference for one specific neurophysiological tool which is the measurement of cardiovascular activity, as it has been found that changes in heart rate are an excellent indicator for anxiety (Felnhofer et al. 2014). A number of other psychophysiological tools have also been applied to measure arousal (i.e. EDA and respiration), but in every single study in this research stream the measurement of changes in cardiovascular activity was included as well. The potential gap we can identify here though is the lack of studies which applied brain-imaging tools to capture the underlying neuronal activations. Only one study (i.e. Kim et al. 2005) utilized EEG to measure brain activation, but did so in combination with a wealth of other, psychophysiological, tools. Therefore, we would expect that future research endeavors in this field should attempt to apply brain-imaging tools which can show overall activations (e.g. EEG or TCD) and then find the specific brain areas which are activated utilizing fMRI. Utilizing this approach could also show whether changes in heart rates and other arousal-related measures are actually caused by the anxiety-related components of a virtual setting or whether they are related to the general exposure to virtuality which can also cause significant changes in arousal.

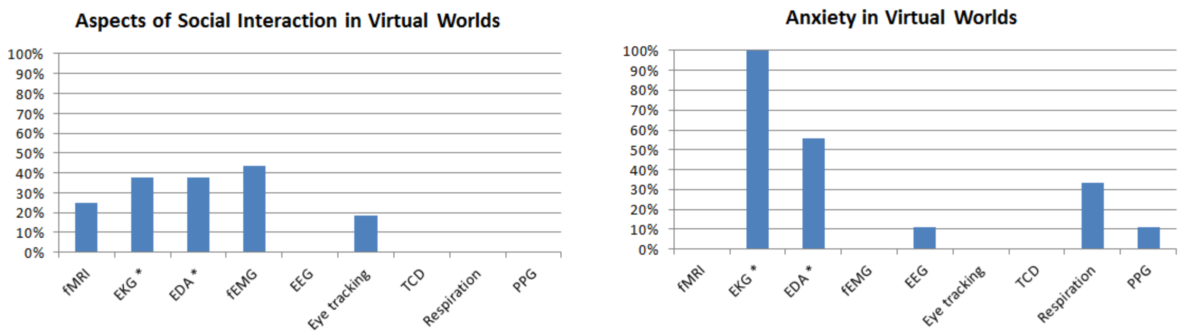


Figure 13: Neurophysiological Tools applied in Research Streams 5 and 6

With regards to "*Representation in Virtual Worlds*" (Figure 14) we can see that this research stream is still in development and studies in this area so far only utilized a limited range of neurophysiological tools. Interestingly though, psychophysiological tools and brain-imaging tools (in this case only fMRI) have both been applied to an almost equal extent. It has to be noted in this context that virtual representations of humans have been frequently utilized as stimulus material in studies focused on *Social Interaction* to be able to more easily control facial expressions which were then presented to participants. Therefore, experiences with the application of fEMG and eyetracking in combination with virtual representations have already been made, but the main focus in these studies was not to investigate the qualities of virtual characters to represent actual humans. Therefore, there are still many opportunities left to utilize a wealth of tools in this field in order to create novel contributions. Research into "*Agency / Self-Involvement*" (Figure 14) is definitely more balanced when it comes to the application of a variety of neurophysiological tools. Reflecting the overall development in the application of neurophysiological tools, fMRI has become the most prominent tool utilized for investigation in this area, though a number of psychophysiological tools remain important as well. Combined applications of tools which do not influence each other based on their measurement approach might be interesting in this area (still difficult for fMRI as discussed before), e.g. measurements of cardiovascular activity and/or electrodermal activity in combination with tools measuring brain activity like EEG and TCD in order to track arousal in several ways.

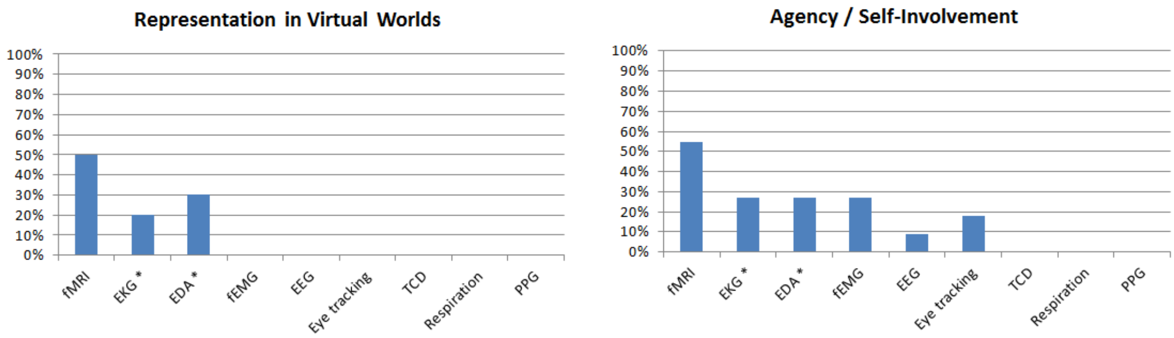


Figure 14: Neurophysiological Tools applied in Research Streams 7 and 8

As opposed to studies interested in *Anxiety*, studies interested in the "*Effects of virtual violence Exposure*" (Figure 15) most frequently applied measurements of electro-dermal activity to measure arousal instead of utilizing measurements of cardiovascular activity for this purpose. An alternative which might be suitable for future studies not yet applied in this context would be the measurement of pupil size as part of an eyetracking approach which has already been used to measure arousal in other areas (e.g. Mojzisch et al. 2006; Alcañiz et al. 2009; Schrammel et al. 2009).

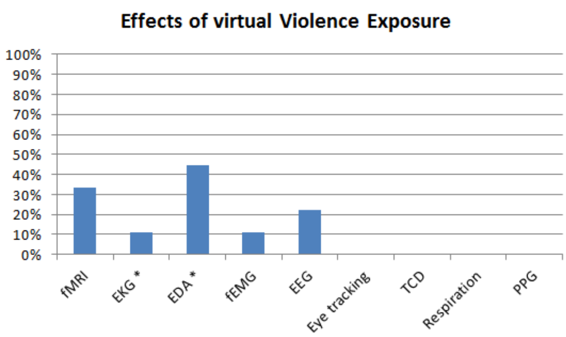


Figure 15: Neurophysiological Tools applied in Research Stream 9

7. Conclusion

The **first contribution** we wanted to make was the *identification of relevant research questions* which could be the basis for future investigations. We did so especially in the last chapter of this thesis, creating a potential research agenda for virtual worlds research applying neurophysiological tools. Yet, the results of our review we presented in the previous chapter, which we then consequently used as the basis to create this research agenda, could lead to prosperous research endeavors on their own. Closing the gaps in previous research we highlighted in the last part of this chapter would be a first step, but of course only represents an of the various research questions that could emerge from these previous findings.

The **second contribution** we wanted to make is to create a review of past research in order to create an overview of the major contributions to virtual worlds research that have been made utilizing neurophysiological tools. This overview is the main part of chapter 5 ("Contributions of previous research"), though further theoretical foundations can also be found in the third chapter ("Theoretical Foundation") were we discussed the definition of a virtual world and introduced neurophysiological tools often applied in IS research.

The **third contribution** we made was giving an overview of the different fields and types of contributions which neurophysiological tools have been applied to in order to create a better understanding for their potential uses. We tried to establish this contribution mainly in the fifth chapter where we showed which tools have been used most frequently and in which combinations, in the context of which types of topics they have been used ("Main Research Streams") and for which types of contributions they have been used ("Contributions of previous Research"). In addition, as part of this chapter, we have shown which tools have been most prevalent in the context of the nine different research streams we had introduced before.

References

Alcañiz, M., Rey, B., Tembl, J., and Parkhutik, V. 2009. “A Neuroscience Approach to Virtual Reality Experience Using Transcranial Doppler Monitoring,” *Presence: Teleoperators and Virtual Environments* (18:2), pp. 97–111.

Bainbridge, W. S. 2004. *Berkshire encyclopedia of human-computer interaction*: *When science fiction becomes science fact*, Great Barrington, Mass: Berkshire Publ. Group.

Bainbridge, W. S. 2007. “The Scientific Research Potential of Virtual Worlds,” *Science* (317:5837), pp. 472–476.

Bartle, R. A. 2004. *Designing Virtual Worlds*, Berkeley, Calif: New Riders.

Bell, M. W. 2008. “Toward a Definition of "Virtual Worlds",” *Journal of Virtual Worlds Research* (1:1).

Blascovich, J., Loomis, J., Beall, A. C., Swinth, K. R., Hoyt, C. L., and Bailenson, J. N. 2002. “Immersive Virtual Environment Technology as a Methodological Tool for Social Psychology,” *Psychological Inquiry* (2:13), pp. 103–124.

Castronova, E. 2006. *Synthetic worlds*: *The business and culture of online games*, Chicago [u.a.]: Univ. of Chicago Press.

Cooper, H. M. 1988. “Organizing knowledge syntheses: A taxonomy of literature reviews,” *Knowledge in Society* (1:1), pp. 104–126.

Davis, A., Khazanchi, D., Murphy, J., Zigurs, I., and Owens, D. 2009. “Avatars, People and Virtual Worlds: Foundations for Research in Metaverses,” *Journal of the Association for Information Systems* (2:10), pp. 90–117.

Dimoka, A., Banker, R. D., Benbasat, I., Davis, F. D., Dennis, A. R., Gefen, D., Gupta, A., Ischebeck, A., Kenning, P. H., Pavlou, P. A., Müller-Putz, G., Riedl, R., Vom Brocke, J., and Weber, B. 2012. “On the Use of Neurophysiological Tools in IS Research: Developing a Research Agenda for NeuroIS,” *MIS Quarterly* (36:3), pp. 679–702.

Dimoka, A., Pavlou, P. A., and Davis, F. D. 2007. “Neuro-IS: The Potential of cognitive Neuroscience for Informations Systems Research,” in *Proceedings of the International Conference on Information Systems, ICIS 2007*, Association for Information Systems (ed.), Montreal, Quebec, Canada. December 9-12, pp. 1–20.

Dimoka, A., Pavlou, P. A., and Davis, F. D. 2010. “NeuroIS: The Potential of Cognitive Neuroscience for Information Systems Research,” *Information Systems Research* (22:4), pp. 687–702.

Felnhofer, A., Kothgassner, O. D., Hetterle, T., Beutl, L., Hlavacs, H., and Kryspin-Exner, I. 2014. “Afraid to be there? Evaluating the relation between presence, self-reported anxiety, and heart rate in a virtual public speaking task,” *Cyberpsychology, behavior and social networking* (17:5), pp. 310–316.

Guadagno, R. E., Blascovich, J., Bailenson, J. N., and Mccall, C. 2007. “Virtual Humans and Persuasion: The Effects of Agency and Behavioral Realism,” *Media Psychology* (10), pp. 1–22.

Johnson, M. J., Chahal, T., Stinchcombe, A., Mullen, N., Weaver, B., and Bédard, M. 2011. "Physiological responses to simulated and on-road driving," *International Journal of Psychophysiology* (81:3), pp. 203–208.

Kim, Y. Y., Kim, H. J., Kim, E. N., Ko, H. D., and Kim, H. T. 2005. "Characteristic changes in the physiological components of cybersickness," *Psychophysiology* (0:0), pp. 050826083901001.

Kindness, P., Mellish, C., and Masthoff, J. 2013. "How Virtual Teammate Support Types Affect Stress," in *2013 Humaine Association Conference on Affective Computing and Intelligent Interaction (ACII),* Geneva, Switzerland, pp. 300–305.

Kotlyar, M., Donahue, C., Thuras, P., Kushner, M. G., O'Gorman, N., Smith, E. A., and Adson, D. E. 2008. "Physiological response to a speech stressor presented in a virtual reality environment," *Psychophysiology* (45:6), pp. 1034–1037.

Levy, Y., and Ellis, T. J. 2006. "A Systems Approach to Conduct an Effective Literature Review in Support of Information Systems Research," *Informing Science* (9:181-212).

Lim, S., and Reeves, B. 2010. "Computer agents versus avatars: Responses to interactive game characters controlled by a computer or other player," *International Journal of Human-Computer Studies* (68:1-2), pp. 57–68.

Meehan, M., Insko, B., Whitton, M., and Brooks, F. P. 2002. "Physiological measures of presence in stressful virtual environments," in *Proceedings of ACM SIGGRAPH 2002*: *[July 21 - 26, 2002, San Antonio, TX],* San Antonio, Texas, New York, NY: ACM, pp. 645–652.

Meehan, M., Razzaque, S., Insko, B., Whitton, M., and Brooks, F. P. 2005. "Review of Four Studies on the Use of Physiological Reaction as a Measure of Presence in StressfulVirtual Environments," *Applied Psychophysiology and Biofeedback* (30:3), pp. 239–258.

Messinger, P. R., Stroulia, E., and Lyons, K. 2008. "A typology of Virtual Worlds: Historical Overview and Future Directions," *Journal of Virtual Worlds Research* (1:1).

Milgram, P., and Kishino, F. 1994. "A Taxonomy of Mixed Reality Visual Displays," *IEICE TRANSACTIONS on Information and Systems* (E77-D:12), pp. 1321–1329.

Mojzisch, A., Schilbach, L., Helmert, J. R., Pannasch, S., Velichkovsky, B. M., and Vogeley, K. 2006. "The effects of self-involvement on attention, arousal, and facial expression during social interaction with virtual others: a psychophysiological study," *Social neuroscience* (1:3-4), pp. 184–195.

Moore, K., Wiederhold, B. K., Wiederhold, M. D., and Riva, G. 2002. "Panic and Agoraphobia in a Virtual World," *CyberPsychology & Behavior* (5:3), pp. 197–202.

Nelson, B., Ketelhut, D., Clarke, J., Bowman, C., and Dede, C. 2005. "Design-based research strategies for developing a scientific inquiry curriculum in a multi-user virtual environment," *Educational Technology* (45:1), pp. 21–28.

OECD 2011. "Virtual Worlds: Immersive Online Platforms for Collaboration, Creativity and Learning," *OECD Digital Economy Papers* 184, OECD (ed.).

Persky, S., and Blascovich, J. 2008. “Immersive Virtual Video Game Play and Presence: Influences on Aggressive Feelings and Behavior,” *Presence: Teleoperators and Virtual Environments* (17:1), pp. 57–72.

Ravaja, N., Saari, T., Salminen, M., Laarni, J., and Kallinen, K. 2006a. “Phasic Emotional Reactions to Video Game Events: A Psychophysiological Investigation,” *Media Psychology* (8:4), pp. 343–367.

Ravaja, N., Saari, T., Turpeinen, M., Laarni, J., Salminen, M., and Kivikangas, M. 2006b. “Spatial Presence and Emotions during Video Game Playing: Does It Matter with Whom You Play?” *Presence: Teleoperators and Virtual Environments* (15:4), pp. 381–392.

Rey, B., Alcañiz, M., Tembl, J., and Parkhutik, V. 2010. “Brain activity and presence: a preliminary study in different immersive conditions using transcranial Doppler monitoring,” *Virtual Reality* (14:1), pp. 55–65.

Riedl, R., Banker, R. D., Benbasat, I., Davis, F. D., Dennis, A. R., Dimoka, A., Gefen, D., Gupta, A., Ischebeck, A., Kenning, P., Müller-Putz, G., Pavlou, P. A., Straub, D. W., Vom Brocke, J., and Weber, B. 2010. “On the Foundations of NeuroIS: Reflections on the Gmunden Retreat 2009,” *Communications of the Association for Information Systems* (27), pp. 243–264.

Riedl, R., Mohr, Peter N. C., Kenning, P. H., Davis, F. D., and Heekeren, H. R. 2014. “Trusting Humans and Avatars: A Brain Imaging Study Based on Evolution Theory,” *Journal of Management Information Systems* (30:4), pp. 83–114.

Schrammel, F., Pannasch, S., Graupner, S.-T., Mojzisch, A., and Velichkovsky, B. M. 2009. “Virtual friend or threat? The effects of facial expression and gaze interaction on psychophysiological responses and emotional experience,” *Psychophysiology* (46:5), pp. 922–931.

Sherman, W. R., and Craig, A. B. 2003. *Understanding virtual reality*: *Interface, application, and design*, San Francisco, CA: Morgan Kaufmann.

Soussignan, R., Chadwick, M., Philip, L., Conty, L., Dezecache, G., and Grèzes, J. 2013. “Self-relevance appraisal of gaze direction and dynamic facial expressions: effects on facial electromyographic and autonomic reactions,” *Emotion (Washington, D.C.)* (13:2), pp. 330–337.

Vom Brocke, J., and Liang, T.-P. 2014. “Guidelines for Neuroscience Studies in Information Systems Research,” *Journal of Management Information Systems* (30:4), pp. 211–234.

Webster, J., and Watson, R. T. 2002. “Analyzing the Past to Prepare for the Future: Writing a Literature Review,” *MIS Quarterly* (26:2), pp. xiii–xxiii.