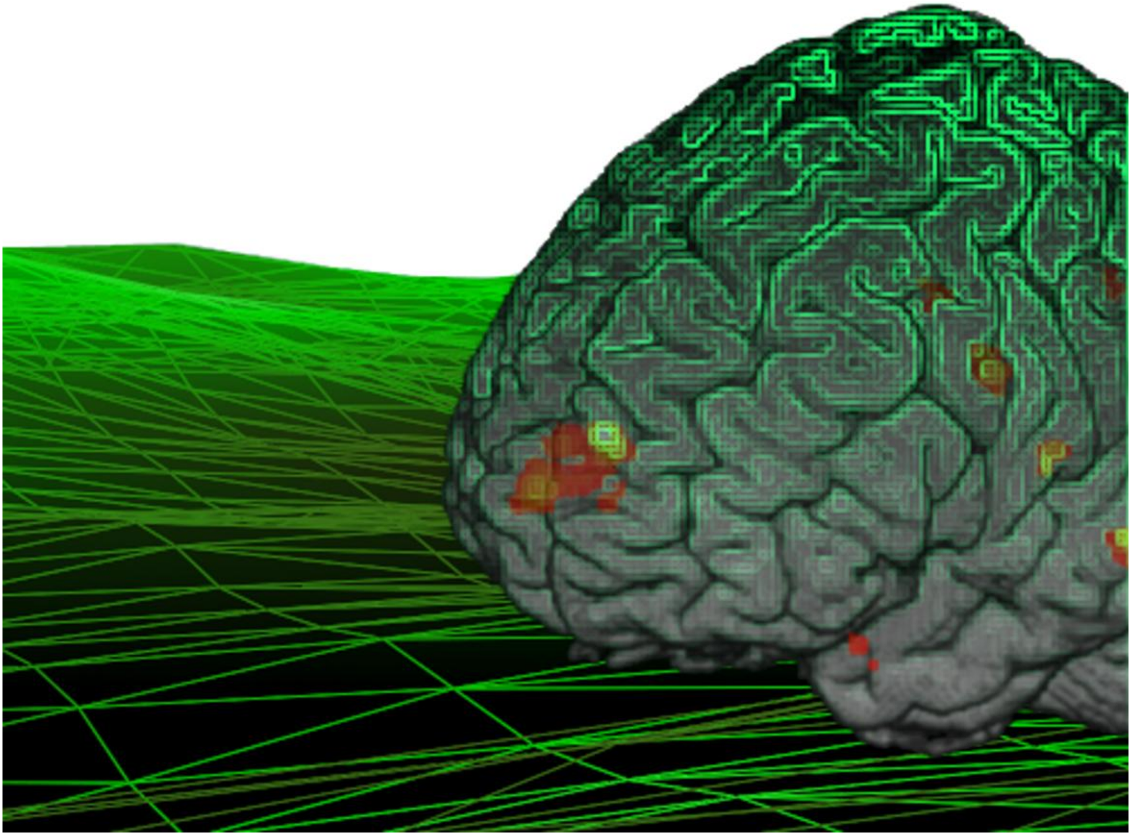

# Human brains and virtual realities

## Computer-generated presence in theory and practice

Daniel Sjölie

**Department of Computing Science**
Umeå 2013

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PhD Thesis, May 2013

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# Abstract

A combined view of the human brain and computer-generated virtual realities is motivated by recent developments in cognitive neuroscience and human-computer interaction (HCI). The emergence of new theories of human brain function, together with an increasing use of realistic human-computer interaction, give reason to believe that a better understanding of the relationship between human brains and virtual realities is both possible and valuable. The concept of "presence", described as the subjective feeling of being in a place that feels real, can serve as a cornerstone concept in the development of such an understanding, as computer-generated presence is tightly related to how human brains work in virtual realities.

In this thesis, presence is related both to theoretical discussions rooted in theories of human brain function, and to measurements of brain activity during realistic interaction. The practical implications of such results are further developed by considering potential applications. This includes the development and evaluation of a prototype application, motivated by presented principles.

The theoretical conception of presence in this thesis relies on general principles of brain function, and describes presence as a general cognitive function, not specifically related to virtual realities. Virtual reality (VR) is an excellent technology for investigating and taking advantage of all aspects of presence, but a more general interpretation allows the same principles to be applied to a wide range of applications.

Functional magnetic resonance imaging (fMRI) was used to study the working human brain in VR. Such data can inform and constrain further discussion about presence. Using two different experimental designs we have investigated both the effect of basic aspects of VR interaction, as well as the neural correlates of disrupted presence in a naturalistic environment.

Reality-based brain-computer interaction (RBBCI) is suggested as a concept for summarizing the motivations for, and the context of, applications building on an understanding of human brains in virtual realities. The RBBCI prototype application we developed did not achieve the set goals, but much remains to be investigated and lessons from our evaluation point to possible ways forward. A developed use of methods and techniques from computer gaming is of particular interest.

# Sammanfattning

Ett kombinerat perspektiv på den mänskliga hjärnan och datorgenererade virtuella verkligheter motiveras av den senaste utvecklingen inom kognitiv neurovetenskap och människa-datorinteraktion (MDI). Framväxten av nya teorier om den mänskliga hjärnan, tillsammans med en ökande användning av realistisk människa-datorinteraktion, gör det troligt att en bättre förståelse för relationen mellan mänskliga hjärnor och virtuella verkligheter är både möjlig och värdefull. Begreppet "närvaro", som i detta sammanhang beskrivs som den subjektiva känslan av att vara på en plats som känns verklig, kan fungera som en hörnsten i utvecklingen av en sådan förståelse, då datorgenererad närvaro är tätt kopplat till hur mänskliga hjärnor fungerar i virtuella verkligheter.

I denna avhandling kopplas närvaro både till teoretiska diskussioner grundade i teorier om den mänskliga hjärnan, och till mätningar av hjärnans aktivitet under realistisk interaktion. De praktiska konsekvenserna av sådana resultat utvecklas vidare med en närmare titt på potentiella tillämpningar. Detta inkluderar utveckling och utvärdering av en prototypapplikation, motiverad av de presenterade principerna.

Den teoretiska diskussionen av närvaro i denna avhandling bygger på allmänna principer för hjärnans funktion, och beskriver känslan av närvaro som en generell kognitiv funktion, inte specifikt relaterad till virtuella verkligheter. Virtuell verklighet (virtual reality, VR) är en utmärkt teknik för att undersöka och dra nytta av alla aspekter av närvaro, men en mer allmän tolkning gör att samma principer kan tillämpas på ett brett spektrum av applikationer.

Funktionell hjärnavbildning (fMRI) användes för att studera den arbetande mänskliga hjärnan i VR. Sådant data kan informera och begränsa en vidare diskussion av närvaro. Med hjälp av två olika försöksdesigner har vi har undersökt både effekten av grundläggande aspekter av VR-interaktion, och neurala korrelat av störd närvaro i en naturalistisk miljö.

Verklighets-baserad hjärna-dator interaktion (reality-based brain-computer interaction, RBBCI) föreslås som ett begrepp för att sammanfatta motiv och kontext för applikationer som bygger på en förståelse av den mänskliga hjärnan i virtuella verkligheter. Den prototypapplikation vi utvecklade uppnådde inte de uppsatta målen, men mycket återstår att utforska och lärdomar från vår utvärdering pekar på möjliga vägar framåt. En vidare användning av metoder och tekniker från dataspel är speciellt intressant.

# Preface

This thesis consists of an introductory overview of the conducted research, and the following papers:

**Paper I:** Daniel Sjölie and Lars-Erik Janlert. *Mind the brain: The Potential of Basic Principles for Brain Function and Interaction.* Report UMINF 13.04, Department of Computing Science, Umeå University, 2013. Submitted.

**Paper II:** Daniel Sjölie. Presence and general principles of brain function. *Interacting with Computers*, vol. 24, no. 4, pp. 193 – 202, 2012. doi:10.1016/j.intcom.2012.04.004.

**Paper III:** Daniel Sjölie, Kenneth Bodin, Eva Elgh, Johan Eriksson, Lars-Erik Janlert and Lars Nyberg. Effects of Interactivity and 3D-motion on Mental Rotation Brain Activity in an Immersive Virtual Environment. In *Proc. CHI 2010*, pp. 869-878, ACM Press, 2010.

**Paper IV:** Daniel Sjölie, Grégoria Kalpouzos and Johan Eriksson. *Capturing neural correlates of disrupted presence in a naturalistic virtual environment.* Report UMINF 13.05, Department of Computing Science, Umeå University, 2013. Submitted.

**Paper V:** Daniel Sjölie. Adaptive games for cognitive training: Lessons measuring arousal with EEG. Accepted to the *CHI 2013 Workshop on Games User Research*, Paris, France, 2013.

In addition to the papers included in this thesis the following papers have been produced during the PhD-studies:

1. Daniel Sjölie, Kenneth Bodin, Johan Eriksson, and Lars-Erik Janlert. Using brain imaging to assess interaction in immersive VR. In *Challenges in the Evaluation of Usability and User Experience in Reality Based Interaction*, proceedings for the CHI 2009 Workshop on RBI Evaluation, Boston, Massachusetts, USA, 2009.
2. Daniel Sjölie. *The brain and interaction in a multimodal reality.* Report UMINF 09.09, Department of Computing Science, Umeå University, 2009.

3. Grégoria Kalpouzos, Johan Eriksson, Daniel Sjölie, Jonas Molin, and Lars Nyberg. Neurocognitive Systems Related to Real-World Prospective Memory. *PLoS ONE,* vol. 5, no. 10, p. e13304, 2010. doi:10.1371/journal.pone.0013304.

4. Daniel Sjölie. *Cognitive Rehabilitation with Realistic and Adaptive Computerized Cognitive Training: A Selective Interdisciplinary Review.* Report UMINF 13.03, Department of Computing Science, Umeå University, 2013.

5. Daniel Sjölie. Reality-Based Brain-Computer Interaction. Presented at the *CHI 2010 Workshop on Brain, Body and Bytes: Psychophysiological User Interaction*, Atlanta, Georgia, USA, 2010.

6. Daniel Sjölie. *Reality-Based Brain-Computer Interaction.* Licentiate thesis. Report UMINF 11.05, Department of Computing Science, Umeå University, 2011.

7. Jonas Persson, Agneta Herlitz, Jonas Engman, Arvid Morell, Daniel Sjölie, Johan Wikström, and Hedvig Söderlund. *Remembering our origin: sex differences in spatial memory are reflected in sex differences in hippocampal lateralization.* Submitted.

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# Acknowledgments

The seeds to the work presented in this thesis were planted during my time at VRlab. As a research engineer at VRlab, I became intimately familiar with virtual reality (VR), and the kind of research projects that VR excels at. You get a special kind of appreciation for concepts such as “presence” when you suddenly react with surprise when your hands go through the (virtual) table, after having spent several hours in VR, testing features that you have developed yourself. I want to thank Kenneth Bodin for giving me the opportunity to work with VR, as the director of VRlab, and Anders Backman for his essential role in the development of the systems we used.

I have always been very interested in cognition and in how the human brain works, and when VRlab got involved in the Swedish Brain Power research program, through Gösta Bucht, and a position as PhD student opened up, I was hooked. Kenneth Bodin and Eva Elgh were heavily involved from the start, and Lars Nyberg soon got involved. Through Eva and Lars the connection between VR and cognitive neuroscience, central to this work, was firmly established. I particularly want to thank Lars for bringing me into the brain imaging research group at the physiology department, and everyone else in that group for welcoming me.

As I moved from being a research engineer to becoming a PhD student, Lars-Erik Janlert joined in as my primary supervisor, and Johan Eriksson became my associate supervisor. Together with Eva, Johan was deeply involved in our first fMRI study, and he has been my primary source of advice and guidance for methodical and practical issues ever since. I also want to thank Olle Hilborn, Jonas Molin and Grégoria Kalpouzos for their involvement in our second fMRI study, and Micael Andersson and Anne Larsson for help with data analysis and equipment setup in both fMRI studies.

Most of the papers I have written have been greatly improved by comments from both Lars-Erik and Johan. While Lars-Erik often comes up with interesting and developing questions of a more philosophical nature (which I love) Johan is often more pragmatic, telling me straight up what does and does not work. It is a good combination.

In the everyday development of my thoughts I have been very glad to often have Erik Billing nearby. Our shared interest in cognition and a computational perspective on intelligence and brain function has sparked many interesting discussions, and a good number of traded references and factoids. I also want to thank Ola Ringdahl for being a good and helpful neighbor, whether it is for providing company at lunches or for assisting with the details of writing a thesis in LyX.

Finally, I want to thank my wife, Johanna. Even though it may be that I sometimes do my best writing after midnight, most of the time I appreciate your efforts to get me to sleep in the night and get up in the morning. And I definitely appreciate that you still tolerate me when I don't.

Thank you.

Umeå, April 2013
*Daniel Sjölie*

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# Chapter 1

# Introduction

The central theme of this thesis is how an understanding of (human) brain function in realistic (virtual) environments can provide a foundation for the development of computer applications deliberately designed for the human brain; that is, designed with an understanding of how aspects of an application (can) affect the working brain, and how one might interpret and adapt to brain measurements. Experience with everyday reality is increasingly recognized as the basis for cognition. The human brain has developed to support interaction with reality, and humans are experts at dealing with phenomena and objects from the real world. Together with the growing capabilities of modern computers, this drives a development within human-computer interaction (HCI) towards increasingly realistic interaction.

The use of realistic interaction is particularly important for applications that relate directly to skill in the real world; in contrast to skill with the computer application itself. The use of computer applications for training or rehabilitation of everyday skills is a prime example. Virtual reality (VR) applications in particular focus on the creation of realistic experiences that allow for transfer to the real world (Rizzo et al., 2004).

## 1.1 Why human brains?

Today computers and computer applications are everywhere around us. They are part of our everyday environment. This means that it is increasingly relevant for HCI to understand how humans, and their brains, work in general. The range of options available when designing HCI applications today is vast, compared to just a decade ago. The limitations on what you can and should do are increasingly found in aspects outside of the computer. In computer applications designed to interact with humans, this makes human nature, and basic principles of human brain function, one of the most important constraints on design and development. Computer applications may also play an important role in supporting the human brain and cognition, for example, through rehabilitation and training of cognitive functions. This aspect is becoming increasingly important as dementia and cognitive decline are becoming serious issues with an aging global population (Hebert et al., 2013).

Striving for an understanding of the human brain in an HCI context is only helpful if such understanding is possible. Recent theories of cognition and brain function increasingly present a coherent view on what the human brain does. Common themes within such accounts can be summarized and condensed into relatively simple general principles. Keeping such principles in mind makes the consideration of human brains in practical HCI work feasible.

## 1.2 Why virtual realities?

A computer-generated VR environment is the most explicit way to create computer applications that are designed to match the general capabilities of humans, and their brains. The human brain has evolved in interaction with physical reality, providing a basis for key functions such as navigation through space and interaction with physical objects in the surrounding space. VR systems aim to relate directly to such familiar interaction methods by, for example, integrating interactive 3d-graphics and simulated physics with natural interaction hardware, such as head-mounted displays (HMDs) and motion-trackers. A representative example is the use of a motion-tracked HMD coupled with computer-generated 3d-environments and motion-tracked gloves, to allow natural interaction with a 3d-environment populated with simulated physical objects (figure 1.1). Images of the virtual 3d-environment are displayed directly in front of the user's eyes and are updated by tracking the movements of the head to produce the sensation of being able to look around freely in the virtual world. An effort is made, both to make the input to the VR-system realistic and natural (move the head to look around), and to make the output from the VR-system realistic (interactive 3d-graphics). In essence, it is a central goal of virtual reality to "fool the brain" and allow the brain to work as if in a real situation.

An important advantage of managing to fool the brain (and the body, to some extent) is increased **ecological validity**. In this context an "ecology" should be understood as an environment, and ecological validity concerns the ability to transfer results from one environment/ecology to another. High ecological validity means that the constructed environment matches the target environment "closely enough", so that results and observations made in the constructed environment are valid in (transfers to) the target environment. For example, ecologically valid training in a virtual environment (VE) means that whatever the user learns to do in the VE, he or she can also do in the real world. Similarly, ecologically valid results from research using a VE means that these results are valid for how humans, and specifically, their brains, work in everyday life.

Figure 1.1: Classical full-fledged VR-setup, with motion-tracked head-mounted display (HMD) and tracked, grip-sensitive, gloves. In this application the user can move around freely in the world by turning the wheels of the wheelchair. Hands are represented in the virtual world and can be used to grab and move objects with simulated physical properties. The head is motion-tracked with six degrees of freedom, allowing the user to look around freely by moving the head, for example, to look under the table. This image is from an earlier VR-project in our lab.

## 1.3 Presence

The concept of **presence** has played an important role in virtual reality research and development since the inception of the field, as a kind of “subjective realism”. The sense of presence is usually described as “the sense of being there”, and it is related to the subjective experience of a virtual environment as believable, realistic and engaging (Slater, 2002). Presence is also very closely related to how the brain works, and to how the brain can be said to work in a certain context at a given moment. More recent descriptions of presence as “the ability to do there” and as the selection or acceptance of a hypothesis, are particularly easy to relate to brain function. The ability to “do there” can be directly related to the ability to use motor representations that are already deeply rooted in the brain to interact within the virtual reality (Jäncke, 2009). For instance, the desire to investigate something to the left and turning the head and eyes towards this location is intimately connected in the brain and encoded as efficient and familiar representations (Postma & Barsalou, 2009).

## 1.4 Outline

This thesis proceeds in three steps, starting with a theoretical discussion of presence, grounded in theories of brain function, moving on to discuss actual brain measurements related to presence, and wrapping up by considering applications where the sense of presence play an important role.

The work on the theoretical papers (I and II), as well as the development and evaluation of the prototype application in paper V, was primarily done by me, with guidance and advice from Lars-Erik Janlert and Johan Eriksson. The studies presented in papers III and IV were conducted by larger teams, but I was responsible for the development of the VR systems as well as the data analysis and the writing of the papers, as first author, in both cases.

# Chapter 2

# Presence in theory

This chapter is about the theoretical basis for presence in the brain. An underlying assumption for the perspective put forward here is that presence is a general phenomenon of the (human) brain and of (human) cognition. As such, a good portion of this chapter is spent on general theories of brain function. Understanding the brain, as it has developed in interaction with reality, is the foundation both for knowing how the brain is affected in a virtual environment and for understanding how brain measurements may be interpreted in this context (chapter 3). A description of some important general ideas, such as grounding and simulation, is followed by an account of how keeping basic principles of brain function in mind can be helpful to HCI in general (paper I). This is followed by a description of how we might understand important aspect of presence within the framework constituted of the presented principles (paper II).

## 2.1 Grounded simulation principles

One increasingly popular idea about the fundamental benefit of the brain is that it is essentially about the ability to predict the future (Friston, 2003, 2005; Hawkins, 2005; Schacter et al., 2007; Bar, 2007; Friston, 2010). More specifically, it is suggested that the basic function of the brain is to use information from the past to make predictions on what *might* happen in the future. Schacter et al. recently attempted to captured this idea with the concept of the **prospective brain**, claiming that they "find it helpful to think of the brain as a fundamentally prospective organ that is designed to use information from the past and the present to generate predictions about the future" (Schacter et al., 2007, p. 660). This idea can also be described using the concept of **mental simulations** within the framework of grounded cognition (Barsalou, 2008; Postma & Barsalou, 2009). Aspects of these mental simulations are stored in brain areas related to the corresponding modalities, providing a basis for higher-level aspects of simulations. The simulations are **grounded** in the modalities.

For example, the higher-level concept of “color” is related to simulations of seeing color, stored in the areas of the brain related to the actual perception of color; and the concept of “up” is related to simulations of looking up, stored in motor areas. Cognition is described as having a hierarchical structure where concepts and phenomena at higher levels are grounded in lower levels. Mental simulations can be directly related to the idea of prediction as a fundamental function of the brain. Running simulations based on current percepts and current context essentially corresponds to simulating what might happen next.

The idea of the brain as a prospective organ has recently seen increasing support from theories of brain function with explicit descriptions of how dynamic prediction models, potentially corresponding to mental simulations, may be feasibly implemented in the brain. The free-energy principle in particular, has been suggested as a potential unified brain theory with solid foundations in the natural sciences and mathematics, compatible with a family of more specific brain theories (Friston & Stephan, 2007; Huang, 2008; Friston, 2009, 2010). The importance of hierarchies and prediction errors are key aspects in many of these theories. The hierarchical nature of the neocortex is related to the power of hierarchical models (Friston, 2003, 2008) and to the prevalence of hierarchical structure in nature (Hawkins, 2005; George, 2008), providing a basis for representations in the brain based on experience with reality. In such models higher levels correspond to aspects of the environment that are more general and more persistent in time and/or space. Such higher levels provide the *context* for interpretations and predictions at lower levels, for example, by specifying that an animal seen at a dog show can be expected to be a dog. This triggers a cascade of predictions at lower levels: expecting to see four legs, dog hair, certain behavior, etc. The prevalence of top-down feedback connections in the hierarchy of the neocortex matches this line of thinking well. It is when the input to the brain does not match the expectations that information needs to be sent upwards in the hierarchy. That is, when there is a mismatch between the true input and the predicted input. It should be noted that the predictions in question here can never be expected to be perfect; there will always be some difference between the modeled expectation and actual input, and, correspondingly, some information will always flow upwards in the hierarchy.

In paper I, I point to similarities between the theoretical perspective on brain function outlined above and the theoretical framework of activity theory. Activity theory is helpful to relate the somewhat abstract ideas above to real human activities and to previous use of theory in HCI (Kuutti, 1996; Kaptelinin, 1996; Rogers, 2005, 2012). In activity theory human cognition is described as developed through internalization of human activities in the real world (Kaptelinin et al., 1995; Kaptelinin & Nardi, 2006; Holzman, 2006; Wilson, 2009). “You are what you do”, and without action, without interaction with the environment, there can be no mind, no consciousness, and no cognition. Activities, and thus cognition, are also described as being object-oriented, having some potentially real outcome as the driving force for action. This fits nicely with a conception of mental simulations as grounded in interaction with reality, including the simulation of possible future situations as a fundamental aspect of human action.

Particularly interesting for the subject matter of this thesis is how this framework suggests that the brain essentially contains a model of reality, and that brain activity in large part corresponds to experiences that are unexpected or surprising; that is, not correctly predicted. Poor predictions can be caused either by an incomplete knowledge of the phenomenon, or by fundamental unpredictability. Predictions may fail because the model is incomplete, or because the phenomenon resists modeling. Truly random stimuli can never be really expected and thus always give rise to a stronger reaction[1]. If the stimuli are fundamentally predictable however, the brain is excellent at detecting and adapting to these stimuli. This effect can be recognized in many well-known phenomena, such as repetition suppression, habituation, and odd-ball paradigms, commonly employed as reliable effects in cognitive neuroscience studies. Given the hypothesized correspondence between the experienced reality and brain activity there are many ways to produce similar effects in virtual reality applications. Different aspects of the computer-generated reality may be manipulated to be more or less familiar, or more or less predictable[2]. This should correspond directly to increased brain activity in the areas of the brain where such aspect are modeled.

The proponents of these theories are not shy about their potential. Karl Friston writes that “one can see easily how constructs like memory, attention, value, reinforcement and salience might disclose their simple relationships within this framework” and that “if one looks at the brain as implementing this scheme (minimizing a variational bound on disorder), nearly every aspect of its anatomy and physiology starts to make sense” (Friston, 2009, p. 293).

In paper I, I suggest that the concept of **grounded simulation** may be used to get a rough but useful sense of central aspects of the theories presented above. One may take as basic principles 1) predicting and simulating how something may be (in the future) is the basis for cognition, and 2) everything humans learn must fit into existing structures that are ultimately grounded in reality. These principles can be derived from the free-energy principle, but they may be considerably easier to get an intuition for, in particular when interpreted in terms of mental simulations. Strongly condensed, these principles may be formulated as simulation and grounding, or together as grounded simulations. Human cognition and the brain can be considered to be all about grounded simulations.

---

[1] The real “problem” is with random *timing*. If the timing is familiar but not the outcome, we can make predictions with a given uncertainty about the outcome, such as predicting the possible outcomes of a thrown dice. But if the dice suddenly starts to move with no warning we have no way to predict and prepare for this.

[2] In this context, fundamental (un)predictability is tightly related to data compressibility. Data that can be compressed can in essence be predicted by the compression algorithm, while data that cannot be compressed is truly random and unpredictable (Chaitin, 2006).

### 2.1.1 Understanding reality

One of the primary points of paper I is to demonstrate how common themes and basic principles can be used to tie different concepts and theories from several disciplines together. How concepts are connected to other concepts, and exactly how they are interpreted, can depend greatly on the background of the reader, and the current perspective. This section gives a few additional examples of how concepts may be related to each other.

In many ways predictions, simulations, activities, imagination, presence, understanding, and subjective reality are very closely related. Experience and familiarity with interaction in a certain context is the basis for all of these. Predictions and simulations can be considered to be essentially the same thing, given the view that the brain makes predictions based on simulations, and that simulations may be implemented using prediction models. Activities are more explicitly grounded in the real world, but since simulations are based on real-world experience, and since activities are partly internalized, this border is also very blurred. Human imagination can be considered to be directly related to dynamic simulations of "what might be", based on internalized activities, etc. Presence is tightly related to the ability to match sensible and familiar simulations, grounded in real activities, to the current environment, and such simulations are the basis for understanding anything, including reality.

Understanding something means that one knows how to interact with it, what actions one could take, and what the result might be. Understanding of a spatial location such as "to the left and a bit down" may be essentially related to collected representations of how to act in relation to this location, for example, how to look at it and how to reach for it (Postma & Barsalou, 2009). These are actions with specific neural representations in the brain, and this reasoning connects directly to the view that even abstract concepts are rooted in the sensory-motor system of the brain (Gallese & Lakoff, 2005; Jäncke, 2009).

Understanding something, as described above, also underlies the perception of something as "real". To quote Hawkins, "predictability is the very definition of reality" (Hawkins, 2005, p. 128). It may be clarifying to consider the opposite of reality; the unreal. If something is unreal it means that it does not fit into the current understanding of the world, it is inconsistent with the patterns one has learned to recognize, and there is no basis for making predictions about this phenomenon. Depending upon how large the deviation from the familiar is, this may lead to confusion, breaks in presence, and/or a forced adaptation of the models for what is familiar: that is, learning.

## 2.2 General implications for HCI

Keeping basic principles of brain functions, such as those summarized by grounded simulation, in mind during design and development of computer applications for humans can be greatly beneficial. Paper I relates principles such as grounded simulation to human-computer interaction and illustrates their potential, for example, by relating to the theoretical framework of activity theory in order to connect basic principles to a wider context, and to established use of theory within HCI. Grounded simulation principles may provide a simpler or more suitable entry point for some practitioners, while providing support for guidelines and communication of results in a manner similar to activity theory (Nardi, 1996; Halverson, 2002).

The diversity of HCI as a field is reflected in the range of theories used within HCI, drawing on several related fields and several different views on human cognition (Rogers, 2012). Basic principles with a firm relation to human brain function and mathematical formulations, such as the free-energy principle, have the potential to provide some common ground. By describing concepts such as affordance (Gibson, 1983, 1986; Norman, 1988, 1999), situated action (Suchman, 1987), and mental models (Rogers et al., 1992) in common terms (see paper I) shared understanding and further development of the theoretical frameworks may be facilitated.

New perspectives that are easily related to existing theory, and that focus on extending and clarifying general themes, have a value simply by being a new way of looking at, and communicating about, old things. In many cases it may be a good idea to continue using the theoretical framework that one knows best, but value can be added by interpreting it in light of grounded simulation principles, not least by facilitating communication with practitioners not familiar with a particular theoretical framework. An expanded grounding of HCI theory is particularly valuable since it is an interdisciplinary field; different explanations may support understanding and applications for researchers and practitioners with diverse backgrounds. Focusing on relatively simple basic principles helps making it feasible for practitioners to actually take the time needed to get acquainted with them. Complexity has often been a major stumbling block for HCI theory, preventing theoretical frameworks from gaining traction (Rogers, 2012).

Some further elaboration on the difference between mental models, as used within HCI (Rogers et al., 1992; Rogers, 2012), and grounded mental simulations, may be illustrative. Mental models were originally suggested as internal constructions corresponding to aspects of the external world, used for prediction and inference (Craik, 1967), and they have been used to explain major aspects of human cognition (Johnson-Laird, 1983). This is clearly similar to the role given to grounded mental simulations above. However, many different conceptualizations of mental models have been presented since these beginnings, and most focus on how specific mental models, relating to specific mental or external phenomena, might work, rather than on general principles for how *all* mental models work, or how they develop in general (Barsalou, 2008). It has come to a state where "Talking about mental models can be a dangerous thing", because there are so many different versions of what a mental model may be (O'Malley & Draper, 1992, p. 73). The conception of grounded mental simulations in this thesis instead focuses on the general nature of mental simulations, and on how they change and develop through hierarchical grounding. The explicit connections to mathematical models and neural implementations both support and restrict further developments of the "grounded simulation" concept, hopefully staving off excessive diversification of the concept.

One practical suggestion based on grounded simulation principles is that the question to ask before all others is: what does the user expect? Research related to these principles provides support for the critical importance of this question, as well as suggestions on how one may begin to answer it. What expectations must, can, or should (not) be violated, and how does this happen? If one understands the expectations of the user, in context, it is possible to guide the user deliberately by introducing information tailored to these expectations. Expectations are largely based on previous experience, and information that reaches higher levels of the user's cognition is based on these expectations. Considering how such information can be seen as prediction errors within a large hierarchy of mental simulations is one example of how grounded simulation principles can provide guidance. The importance of prediction errors is directly related to the general impact of randomness and regularity in interaction, and to the importance of existing mental simulations and familiarity with relevant interaction phenomena. It is worth noting that one does not need to know the details about how a user's mental model is set up in order to take advantage of basic principles when designing interaction systems. Identifying what is familiar and what is predictable is valuable at each level, even if it is only done for parts.

## 2.3 Presence and synchronization

Building upon the same general principles of brain function as above, paper II reasons about how it is possible to understand many of the phenomena generally associated with presence. The basic reasoning is based on a view of the human brain as continually running a simulation of the surrounding environment, as suggested above, trying to match and anticipate the future as well as possible. Such simulations have reached the brain through experience with reality, through prediction errors that force refinements of the dynamic models. The (hypothesized) fact that these mental simulations originate in the real environment leads to an expectation of similarities between actual reality and the simulation in the brain, both in behavior and in structure. When the world the brain currently inhabits is a computer-generated virtual reality, this perspective constitutes the foundation for an interpretation of brain function and brain measurements as directly related to phenomena in and aspects of this virtual reality, such as randomness in the behavior of some virtual phenomenon.

Inherent in the very meaning of the word presence is that something (the subject) may be present in some environment or context. The first question to be considered then, is what the subject may be present in. In the perspective provided by the principles described above the information that reaches any higher levels of the brain (related to persistent phenomena) is related to internal expectations of the brain to an extremely high degree, rather than being anything like direct information from the external environment. One way to think of such expectations is as mental simulations that together create a **subjective mental reality**. This subjective mental reality may be more or less influenced by the current external environment, but it does run on its own, as “a generative model of the world it inhabits” (Friston, 2010, p. 135), to a large degree. Sufficiently so that a reasonable answer to the question of what one might be present in is: the subjective mental reality that is simulated in the brain. Within this perspective, the degree of presence in a certain environment may be considered to be the degree of *synchronization* between this environment and your subjective mental reality.

Synchronization is both a state and a process, and both meanings are relevant in this context. Synchronization as a state can be described as two systems that do the same thing, and produce the same results. In this sense, describing presence in an environment as synchronization with that environment means that the mental simulations that constitute your subjective mental reality match (do the same thing as) phenomena in the candidate environment. For example, presence in an office space may depend on your ability to correctly simulate the result of possible interactions with a pen lying on the desk. Thinking of synchronization as a process, on the other hand, is helpful to understand how the sense of presence develops and changes through interaction with the environment. In particular, it may provide valuable hints about the requirements for and limitations of presence. Synchronization of the subjective mental reality with an external (real or virtual) environment is driven by prediction errors, in relation to current mental simulations. It is by resolving detected mismatches that the synchronization develops, but in order for phenomena in an environment to be successfully synchronized it must be possible to integrate them into the larger hierarchy of mental simulations. That is, the parts making up the phenomenon must be familiar (for example, familiar buttons on a novel remote) and there has to be some context (higher-level simulation) in which the phenomenon fits (for example, using a remote to play a movie).

One implication of this perspective on presence is that brain activity associated with a high level of presence should depend strongly on the specifics of the current environment and task. Conversely, a low level of presence should be related to a mismatch between the actual brain activity and the brain activity required to simulate the environment. If being present in an environment means that your brain is simulating aspects of this very environment, then your brain activity should reflect this, and being present in different environments should lead to corresponding differences in the patterns of brain activity. In the case of reduced or disrupted presence in relation to a specific environment, the “alternate environment”, representing reduced presence, may be a state of general confusion, a more confused version of the “presence environment”, or some form of daydreaming. Such observations are clearly important for the interpretation of studies on the neural correlates of presence, such as the study presented in paper IV. This description also illustrates the importance of VR in creating an environment that can immerse the user and engage their whole brain; a brain developed to simulate and synchronize with complex realistic environments.

In paper II this perspective on presence is further related to previous descriptions of presence, and to potential applications and implications. Hierarchies (grounding) and expectations (simulation) have been emphasized many times before, for example, by describing presence in relation to levels of intentions or activities (Riva et al., 2011), or by pointing to the importance of selecting and maintaining a hypothesis about your environment (Slater, 2002; Slater & Steed, 2000). Neither is describing presence as a general function of the brain (not specific to VR experiences) uncommon (see, among others, Loomis (1992), Biocca (1997) and Riva (2009)). What paper II adds to this picture is a further generalization of the basis of presence in cognition and brain function, as well as additional connections to areas such as physics, evolution and information science. Among other things, this provides additional points of entry for researchers and developers working within the multidisciplinary teams often required for the development of computer applications designed for presence.

As with HCI theory in section 2.2, the general nature of the principles described here makes it relatively easy to relate them to previous accounts of presence. Paper II develops the relation to several such accounts, such as the importance of avoiding "breaks in presence" (Slater & Steed, 2000; Slater, 2002), the ability to use familiar representations to "do there" (Jäncke, 2009), successful transformation of intentions into actions (Riva, 2009; Riva et al., 2011), and the perceptual illusion of non-mediation (Lombard & Ditton, 1997; Riva et al., 2011). For example, the illusion of non-mediation can be related to the absence of (significant) prediction errors, in a well internalized and adapted mental simulation. Any mediating tool that works exactly as predicted gives no prediction errors, if it is well known and correctly simulated, and becomes transparent to the user.

### 2.3.1 Surviving the present

When the human brain is thought of as an organ developed trough interaction with reality, through a combination of evolution and adaptation based on experience, the sense of presence can be related to possibly the most critical function of all: sensing danger and acting to optimize (future) safety. Feeling present in an environment means that you are in sync with your surroundings and ready to act. This is vital to your survival, and being able to detect that this synchronization is flawed should be a very important capability, demanding action or adaptation.

## Summary

A view on the brain as continually striving to simulate the surrounding environment facilitates both a basic understanding of brain function in general, and a conception of presence as related to synchronization with an environment. This view builds on an increasing appreciation for the importance of predicting what might happen next, as a basis for human cognition and brain function.

A user's experience of a VE, or any computer application interface, depends heavily on the user's expectations. The totality of such expectations can be summarized as the user's subjective mental reality. The synchronization between this subjective mental reality and a specific external environment can be said to correspond to the user's degree of presence in this environment.

Two key aspects of this conception of presence, to keep in mind for the rest of this thesis, are:

1. Presence is a general function of cognition, related to your familiarity with and attention to your current environment. It is not specifically related to immersive VR, although VR provides unique opportunities to manipulate and explore all aspects of presence.
2. The brain activity related to presence, and differences in the level of presence, in any specific environment, is tightly related to the actual environment and the current task.

# Chapter 3

# Presence in practice: measurements

In order to move from presence in theory to presence in practice, including practical computer applications, a basis in experimental studies investigating the neural correlates of presence is desirable. We have conducted two studies to investigate different aspects of brain activity in immersive VR environments. Results from the first study are reported in paper III. Results from the second study are reported in paper IV, as well as in Kalpouzos et al. (2010).

The method used in the work presented here is functional magnetic resonance imaging (fMRI). FMRI makes use of the fact that the magnetic properties of oxygenated and deoxygenated blood are different to capture images of the distribution of oxygenated blood in the brain. Such images are related to brain function based on the assumed connection from the delivery of oxygen to areas of the brain (via the blood), to the metabolism in the area, and to local neural activity . This makes it possible to record changes in activity over time in the whole brain, within the limitations set by the fundamental slowness of the measured hemodynamics and the imperfect understanding of the connection between the hemodynamics and the actual information processing (Heeger & Ress, 2002; Haynes & Rees, 2006; Logothetis, 2008). In spite of such limitations, the combination of whole brain coverage, good spatial resolution (a few millimeters), and a decent temporal resolution (a few seconds), makes fMRI the method to beat when it comes to large scale measurements of the working brain. By comparison, electroencephalography (EEG), used in paper V and further described in section 4.3, has poor spatial resolution and only measures activity on the surface of the brain.

Most analysis of fMRI data is based on a statistical evaluation of the differences between images gathered in connection to experimental conditions. Such difference images are called **contrasts**. The most common format for investigating contrasts for fMRI are statistical parametric maps (SPMs) of t-values (Friston et al., 1991). Such a contrast contains a map of all the voxels (volume elements, positioned boxes) in the brain, with the difference between two condition maps scaled with the standard deviation. This corresponds to a value for each voxel in the brain representing how big the difference between conditions is in relation to the general variation at this voxel. Big effect sizes can be caused by large differences in the mean signal or by low variance. Conversely, small effect sizes may be caused by small differences in the mean signal or by high variance.

## 3.1 Brain activity and realistic interaction

In our first fMRI-study, presented in paper III, we investigated the effect of common aspects of realistic and dynamic interaction environments on brain measurements using fMRI. Subjects were presented with a mental rotation task while immersed in a 3d-world. Immersion was achieved by using a head-mounted display (HMD) specifically constructed to be compatible with fMRI. Mental rotation is a well studied task, studied first by Shepard and Metzler (1971) and many times since, including several previous fMRI-studies (Cohen et al., 1996; Tagaris et al., 1997; Mourao-Miranda et al., 2009). This provided a good foundation for interpretation of which brain activity was related to execution of the task in general, and allowed us to focus on the differences in brain activity introduced by our manipulations. In our case, the specific task was to compare a pair of 3d-figures presented inside the 3d-word. The 3d-figures where either identical or mirrored, and they were oriented randomly, necessitating a mental rotation in order to compare them. Brain activity was compared between three different conditions, all with the same basic mental rotation task. The conditions were with or without 3d-motion and/or interactivity. In the first condition the task was conducted completely without motion, in the second condition the task was conducted with an automatic 3d-rotation around the 3d-figures, and in the third condition the subjects were able to control this motion interactively.

The primary motivation for this study was a general need to understand how the brain responds to aspects of a VR environment, in order to enable the use of brain measurements for evaluation of user interaction in realistic environments. Evaluating interaction in realistic interaction environments is a challenge, because of the complexity of the interaction and the freedom often given to users. This is true for many realistic forms of interaction, as described in relation to the framework of reality-based interaction (RBI) (Jacob et al., 2008; Christou et al., 2009), and brain measurements has been suggested as an efficient way to measure variables for user evaluation (Girouard et al., 2008; Hirshfield et al., 2009b,a; Sjölie et al., 2009). However, in order to correctly interpret brain measurements that may be related to, for example, user workload or presence, we need to understand how brain activity is affected by prominent aspects of a VR environment that may not be intended to affect the variables of interest. Such understanding may also be needed for the further development of computer applications that interpret brain measurements in realistic environments, in order to adapt to the user in real-time. This type of application is further

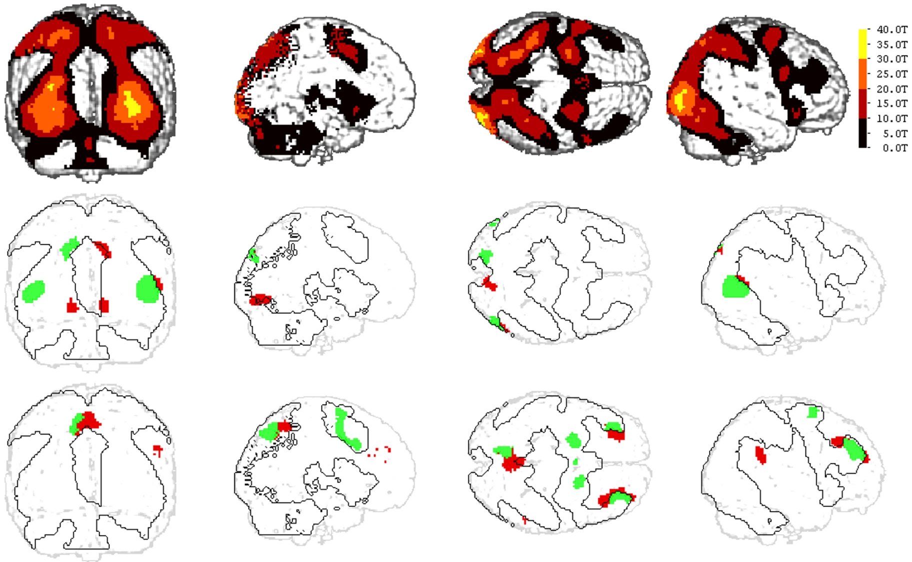

Figure 3.1: Brain areas significantly activated for the mental rotation task in general (top), and areas with increased activity for 3d-motion (middle) and interactivity (bottom). Increased activations are displayed as within (green/bright) or outside (red/dark) of the mental rotation network (black outline). Images are surface renderings showing activations to a depth of 20 mm, with caudal, right medial, dorsal and right lateral views, from left to right. Figure from paper III.

described and motivated in chapter 4.

The mental rotation network, defined as all brain areas with significantly increased activity during mental rotation in all of the conditions, matched previous results well for the most part (figure 3.1). The strong occipital activation in our study is a possible exception, since this area has been inconsistently reported in previous studies. Our interpretation is that this is based on differences in the chosen baseline. Our baseline had no counterpart to the complex 3d-objects rotated during the task, and visual inspection of the 3d-object is a likely interpretation of the occipital activation. This interpretation has some support in earlier work (Mourao-Miranda et al., 2009).

Automatic 3d-motion added little to the measured brain activity and the additions that were detected were restricted to posterior and visual areas of the brain. This result can be explained in relation to grounded simulation principles as the pattern of motion was predictable at lower levels of the brain and thus did not lead to any further prediction errors at higher levels. The effect of interactivity was remarkably different. In this case there were distinct increases in brain activity in the frontal regions of the brain, and it largely overlapped with areas already activated for the mental rotation task in general (figure 3.1). Within the theoretical perspective described in chapter 2 the increased activity from interactivity can be understood as a combination of increased unpredictability in the environment and increased attention to the environment. Both unpredictability and attention lead to an increase in prediction errors, either by making input harder to predict or by making predictions more precise and sensitive. The addition of interaction both makes the entire system more unpredictable (than fixed speed rotation) and motivates the user to pay extra attention to how the observed motions match intended interactions. This suggests that the addition of interaction can be a valuable approach to stimulating more prediction errors and increasing brain activity, potentially facilitating more efficient detection, for example, for diagnosis of cognitive functions. The more frontal nature of the effect of interactivity also fits well with the hierarchical structure of predictions and prediction errors in the theories presented above. Environments that are more dynamic and harder to predict lead to more prediction errors being fed upwards, and to increased activity in higher-level, more frontal, regions.

We did not measure the subjects' sense of presence in the different conditions in our study, but similar conditions have been related to differences in reported presence in other studies. In a study by Clemente et al. (2011) questionnaires were used to compare reported sense of presence for a task conducted either by looking at photographs or a video of a virtual environment (VE), or by interactive navigation through the VE. They showed no significant difference in reported presence between the conditions using photographs and videos, but significant differences between both these conditions and the interactive condition. This provides some support for relating the increased activation in our interactive condition to an increased sense of presence. In terms of the theory presented in chapter 2 and paper II this may be related to synchronization in brain areas related to the in-environment-task, though this is only a speculation at this point.

## 3.2 Neural correlates of disrupted presence

The fundamentally subjective nature of presence makes investigation of the neural correlates non-trivial. When using different designed conditions, like the ones in our first study and the study by Clemente et al. (2011), to investigate neural correlates of presence, it is necessary to complement these conditions with subjective reports of experienced presence (as those collected by Clemente et al). Baumgartner et al. used individual differences in reported presence, together with analysis of connectivity between brain areas, based on a prior hypothesis, to analyze neural correlates of presence in the largest study on the subject to date (Baumgartner et al., 2008). The number of steps required for this analysis illustrates the complexity in capturing this data. One alternative approach is to focus on capturing what happens when the subjective sense of presence changes in a (virtual) environment that objectively stays the same as far as possible. Bouchard et al. (2009; 2010; 2012) demonstrated one such approach by using different narratives to produce differences in presence while

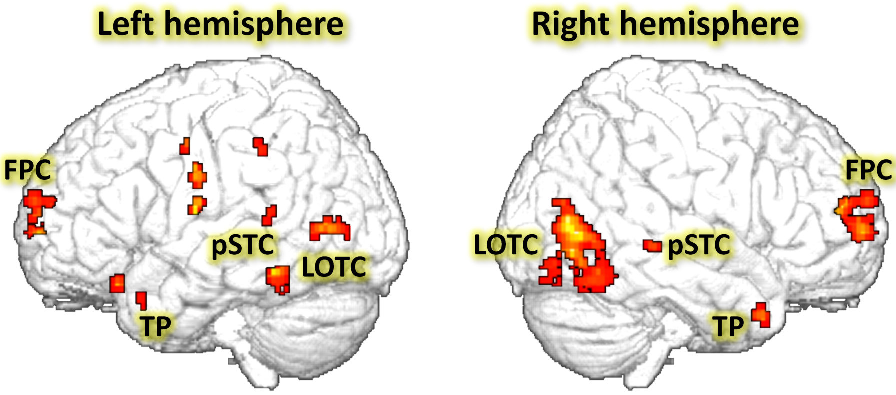

Figure 3.2: Brain areas with significantly increased BOLD-signal for time periods of disrupted presence. FPC = frontopolar cortex, LOTC = lateral occipito-temporal cortex, TP = temporal pole, pSTC = posterior superior temporal cortex. Figure from paper IV.

keeping the VE the same across conditions in other aspects.

In our second fMRI study we focused on capturing the neural correlates of time periods of disrupted presence during an everyday task in a naturalistic (virtual) environment. We used retrospective verbal reports to identify times periods where subjects indicated that something in the environment was "strange" (see, for example, Spiers & Maguire (2006b), for a similar approach). Such strange time periods are interpreted as related to violations of expectations underlying the sense of presence, leading to disrupted presence. Expectation violations affecting presence can also be described as breaks in presence (BIPs), a concept that been used to describe the avoidance of BIPs as central to the maintenance of presence (Slater, 2002; Slater & Steed, 2000).

Our primary findings were increased activity in frontopolar cortex (FPC), lateral occipito-temporal cortex (LOTC), temporal poles (TP), and posterior superior temporal cortex (pSTC), all bilateral (on both sides of the brain). We suggest two interpretations of this activation pattern as particularly interesting: relating it to a self-centered form of mentalizing, or to recurrent forms of grounding for a subjective mental reality that is in sync with a naturalistic VE. These interpretations are not in conflict, but may be seen as different perspectives on the same basic phenomenon. Considering them together may illuminate both perspectives.

Mentalizing is often described as the human ability to perceive and think about the mental states of other people, including motives, emotions, intentions, etc., also described as having a Theory of Mind (Frith & Frith, 2003; Frith, 2007). However, mentalizing has also been related to self-awareness and self-perception (Frith & Frith, 2003; Moriguchi et al., 2006; Frith, 2007), and may be related to the general simulation of agents (humans) with emotions, motives, etc., in a situational context. Although we did not have any other people to mentalize about in our environment, mentalization is of interest in part because of a striking overlap between our results and areas previously related to mentalizing (Frith & Frith, 2003; Spiers & Maguire, 2006a; Frith, 2007), and in part because of the importance of agency and the self in previous accounts of presence (Riva, 2009; Riva et al., 2011). In particular, a study by Spiers and Maguire on spontaneous mentalizing during an interactive real world task bears a clear resemblance to our study, both concerning experimental design and results (Spiers & Maguire, 2006a). While their VE is populated with people and ours is not, both studies use retrospective verbal protocols to investigate subjective experiences during an everyday task in a naturalistic environment, and their results include areas overlapping FPC, LOTC, TP and pSTC. As such, it is possible that our results are related to brain functions common to mentalizing and self-perception, supporting the mental simulation of (aspects of) an agent, self or other, in a realistic environment and situation.

Another interesting interpretation of these results, in light of the theory presented in chapter 2, is that all of these areas can be described as providing context or grounding for mental simulations in ways that are important for a sense of presence: relating the (changing) situation to: the current task and overarching goals (FPC) (Koechlin & Hyafil, 2007), interpretation of (incongruous) visual information (LOTC) (Michelon et al., 2003), emotional integration and evaluation of the context (TP) (Olson et al., 2007), and interaction possibilities (pSTC) (Frith & Frith, 2003; Frith, 2007). Modulation of activity level in these brain areas is consistent with an interpretation of disrupted presence as a re-evaluation of key aspects of a subjective mental reality, updating the synchronization with the virtual environment as previous predictions fail. Together with the self-centered mentalization interpretation this may also suggest that these areas and the aspects they represent are important for the general simulation of an agent in a realistic context. The significance of these regions in the context of a naturalistic VR environment is supported by the variability in subject behavior. These areas are consistently activated in connection with disrupted presence, over a range of different situations within the VE.

These brain imaging results may inform further development of theoretical accounts of presence, making them more precise. For example, the activated brain areas in paper IV point to specific aspects of the subjective mental reality discussed in paper II, that may be particularly important for accepting a complex interaction environment as “reality”.

## Summary

The two fMRI studies presented above represent two different approaches to investigating the neural correlates of presence and realistic interaction. The distinct conditions in the first study make it easy to relate brain activity to environment and task but does not provide any explicit link to presence. The use of “strange” time periods in the second study relies on a theoretical connection to disrupted presence and subjective classification of verbal reports, but provides a possible view of changing presence in an ecologically valid VR scenario.

In light of the theory described in chapter 2, a good understanding of the human brain in virtual realities (and the neural correlates of presence) requires both types of studies. The first study exemplifies of how brain activity depends on important aspects of the environment and task in VR, while the second study contributes to an understanding of what happens when presence changes within a specific, naturalistic, environment and task.

If brain activity related to presence depends on the specifics of the environment, as suggested in this thesis, more studies are required to build a complete picture the neural correlates of presence, but these results make a good contribution to the sketch so far.

# Chapter 4

# Presence in practice: applications

One important goal of the theory developed in chapter 2 and the investigations presented in chapter 3 is to provide support for further development of computer applications that are deliberately designed to work with the brain; deliberately affecting the working brain, and adapting to its (measured) reactions. In this context, the importance of presence can be illustrated by describing presence as the sense that the computer works perfectly with the brain. The standard connection between presence and VR, as exemplified by immersive 3d-graphics and similar technologies, is essentially related to the fact that our brains are intimately familiar with spatial interaction using our body; a familiarity developed through a combination of evolution and experience. In this chapter, I relate this conception of presence to emerging methods and applications within HCI, with a particular focus on the potential for computerized cognitive training. This includes the development and evaluation of an application for adaptive and realistic cognitive training.

## 4.1 Reality-based brain-computer interaction

The framework of reality-based interaction (RBI) has been used to summarize the underlying advantages (and disadvantages) of designing interaction with computers to be similar to interaction with physical reality (Jacob et al., 2008). RBI relates realistic interaction to human awareness of, and skill with, the human body, the current environment, and the current social situation, as well as a naïve human understanding of physics. By making interaction with a computer more like interaction with the real world it becomes possible to use familiar concepts to understand and predict the capabilities and functions of a computerized system. This line of thought can be directly related to the concept of presence; for example, when presence is formulated as “the ability to do there” and related to existing motor representations. Both effective RBI and presence are strongly related to the familiarity of the current environment.

I have suggested the concept of reality-based brain-computer interaction (RBBCI) as a way to summarize central aspects of the development of computer applications that target the human brain (Sjölie, 2010, 2011). Figure 4.1 illustrates the multidisciplinary nature of RBBCI, with primary influences and related areas of research. In terms of practical applications RBBCI builds on a combination of VR (a form of RBI) and adaptive brain-computer interfaces (BCIs).

Adaptive BCIs is a recent example of rising interest in adaptive psychophysiological computing in the HCI community. Measurements from the brain or body, that is, physiological measurements, are increasingly employed as extra input channels for computer applications (Fairclough, 2009; Tan & Nijholt, 2010). These measurements can be related to the psychological state (thus the term psycho-physiological computing) of the user and they can be used to adapt the behavior of the application to psychological states such as frustration, overload, or excitement (Picard, 2000; Daly & Wolpaw, 2008; Tan & Nijholt, 2010; Zander et al., 2010). Brain measurements in particular provide a direct connection to psychological and cognitive state that may be very valuable for applications targeting cognitive training.

The integration of brain measurements into computer applications has traditionally been related to the use of BCIs to enable the user to deliberately control an application "with their mind" (active BCI) (Tan & Nijholt, 2010). The use of similar BCI methods for the passive adaptation of an application has been suggested (Cutrell & Tan, 2007; Girouard, 2009; Zander et al., 2010; Girouard, 2010; Zander & Kothe, 2011; Poel et al., 2012) and recent years has seen a number of promising approaches (Hirshfield et al., 2009b; Plass-Oude Bos et al., 2010; Solovey et al., 2012; Girouard et al., 2013) but such applications are still rare and much remains to be explored. I have, for example, yet to see an application that combines VR and realistic interaction with an adaptive BCI in any explicit manner, although active BCIs have been used together with VR several times (Allison et al., 2012; Scherer et al., 2012). Implicitly, the use of adaptive BCIs in games sometimes involve game worlds with a measure of realism, for example, when using measured alpha wave activity (see section 4.3) to automatically shift the form of the game character in the World of Warcraft (WoW) game (Plass-Oude Bos et al., 2010). Another recent application of adaptive BCIs is the use of functional near-infrared spectroscopy (fNIRS) to detect multitasking in users and adapt the behavior of simulated robots accordingly, requiring less input from users when they are otherwise engaged (Solovey et al., 2011, 2012).

The conception of presence presented in this thesis can be used to relate brain measurements to deliberate manipulations of phenomena in a VE. Essentially, mental simulations develop through internalization to become synchronized with phenomena in the environment. Aspects of phenomena to be synchronized, such as predictability and familiarity, can be related to brain function via properties of the corresponding mental simulations and the process of synchronization.

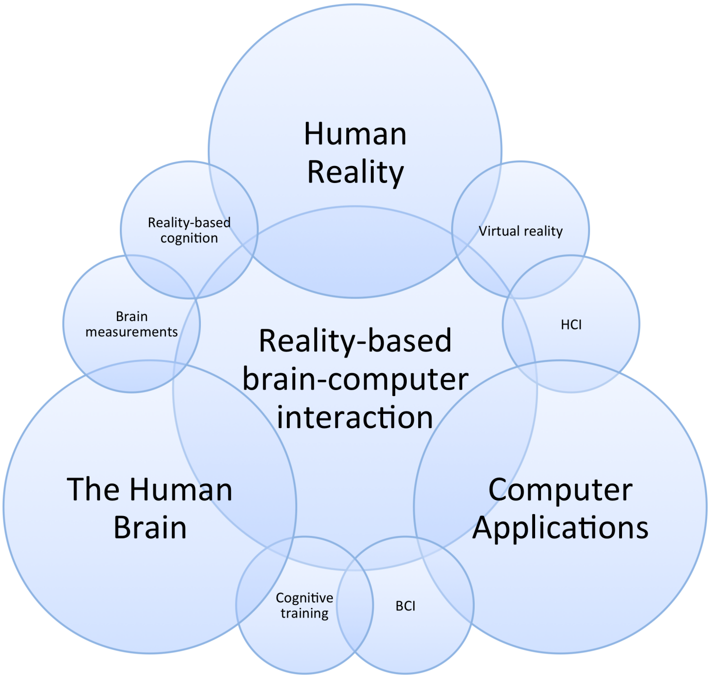

Figure 4.1: Illustration of reality-based brain-computer interaction (RBBCI) in relation to primary influences and related areas of research. Essentially, RBBCI concerns how *computer applications* can be developed for *the human brain* by consideration of *human reality.* The areas shown should be understood as representative examples of how the primary influences are tied together by previous research and existing methods.

Deliberate manipulation of virtual phenomena makes it possible to adapt the computer-generated reality in order to, for example, provoke increased brain activity and facilitate detection and diagnosis, or to optimize the development, restoration, or maintenance of cognitive skills through training. Since the mental simulations in question are presented as the foundation for cognition on all levels, this approach is valid even for abstract mental tasks. This provides a basis for the development of realistic and adaptive computer applications that target cognitive skills and abilities; such as cognitive training, neuropsychiatric rehabilitation or diagnosis of neurodegenerative diseases.

The concept of reality-based brain-computer interaction (RBBCI) is intended to support the development of systems where the computer interacts deliberately with the brain. The input to the brain consists of deliberately constructed computer-generated phenomena in a virtual reality, and the output from the brain consists of brain measurements that can be related to properties of these phenomena in an informed manner. Thus, the computer interacts with the brain without deliberate involvement of the conscious user. To develop an RBBCI application it is necessary to integrate the use of VR techniques and adaptive BCIs with an understanding of how brain activity is affected, both by VR in general and by possible adaptations of VR in particular.

## 4.2 Computer aided cognitive training

Computer aided cognitive training is among the most promising applications to benefit from the collected consideration of human brains and virtual realities presented in this thesis. Cognitive training is based on the idea that it is possible to improve cognitive performance by practicing on certain tasks; tasks that may be implemented using computer applications for computer aided cognitive training. The basic cognitive and neural plasticity of the brain is well supported by previous research, providing a fundamental argument for the feasibility of cognitive training (Dahlin et al., 2008; Erickson et al., 2007; Klingberg, 2010; Li et al., 2008), but the specific constraints on what is possible remain unclear. One important factor for the possible applications of cognitive training is the potential for **transfer**, that is, the potential for improvements on one (trained) task to carry over to improvements on other (untrained) tasks. Transfer to similar tasks is called near transfer while transfer to unrelated tasks is called far transfer.

One form of cognitive training that has attracted much attention is working memory (WM) training. Working memory refers to the capacity to temporarily keep active and manipulate information in memory that is needed for higher cognitive functions (Baddeley, 1992). Working memory capacity, that is, how much information can be held active and manipulated at the same time, predicts performance in a wide range of cognitive tasks, and many neuropsychiatric conditions such as stroke or attention-deficit hyperactivity disorder (ADHD) coincide with impaired WM (Klingberg, 2010). Several studies have shown that performance on specific WM tasks such as 2-back (comparing the last number in a sequence to the one presented 2 steps before) does improve with training, and that this effect does transfer to similar, that is, near transfer, tasks (Klingberg, 2010; Li et al., 2008; Owen et al., 2010; Dahlin et al., 2008). However, the magnitude and range of transfer, in particular the potential for far transfer, remains disputed.

In a study by Owen et al. (2010) 11,430 participants training on cognitive tasks online for several weeks failed to show any general cognitive improvements outside of the tasks that were actually trained. How can this be explained given the previously demonstrated potential for cognitive plasticity and transfer? Can faith in the potential of cognitive training be maintained? The first thing to consider is that the primary goal of the study in question was to investigate potential *general cognitive improvements.* Even though the results include remarks about a lack of transfer even between relatively similar tasks, the potential for near transfer to similar tasks was not developed. Thus, we are encouraged to take a closer look at near transfer, and to focus on how to achieve the necessary overlap and similarity between tasks, and a corresponding overlap in neural correlates. This motivates the use of realistic interaction for computerized cognitive training, and illustrates the need to train the right thing and to create interactive systems with a high degree of ecological validity. RBI in general, and VR in particular, provides a foundation for ecologically valid HCI by building on the user's skills and experiences from reality (Jacob et al., 2008; Rizzo et al., 2004).

A powerful argument for the critical importance of both the amount and the intensity of training can be found in research on expertise. In short, it has been shown that what is needed to become truly skilled is a large amount of training at a deliberately directed and adapted level of intensity and difficulty (Ericsson & Charness, 1994; Ericsson et al., 2007). Humans are not born to become chess masters or elite musicians but "experts are always made, not born" (Ericsson et al., 2007). Deliberate practice must be directed to a level where the training in question includes elements that one is not already skilled with, while at the same time building on elements that one is familiar with. In essence, one needs to make some errors in order to have something to correct and improve, but too many errors will hamper learning. For physical tasks VR applications make it possible to control and recorded interaction exactly, facilitating adaptation, but this becomes problematic as the task becomes increasingly cognitive in nature. This shortcoming can be addressed using a combination of BCIs and an understanding of the human brain and computer-generated presence in virtual realities. Tracking presence using brain measurements is a promising approach to create systems that adapt training automatically, as described with RBBCI.

## 4.3 An RBBCI prototype application

In order to evaluate the RBBCI approach we constructed a system where brain measurements were integrated into a game engine, and used this system to develop a prototype application for adaptive and realistic cognitive training. While fMRI measurements have great advantages for investigating brain function, there are many disadvantages, such as high cost and restricted mobility, when aiming to develop systems for practical use and wide distribution. We chose to move in the other direction, and instead made use of a commercially available and affordable EEG-headset: the Emotiv Epoc (Emotiv Emotiv Corporate, 2011). Applications that depend on tools such as the Epoc to make cognitive training more efficient could potentially be widely spread and make a real impact on, for example, the growing need to combat cognitive decline with an aging population (Hebert et al., 2013). This direction is in line with recent calls for taking BCI-applications from feasibility studies in the lab to practical applications for real-world use (Plass-Oude Bos et al., 2010; Millán et al., 2010).

EEG is based on measuring differences in electrical potential on the scalp that result from electrical currents in the brain (Silva, 2010). These currents are the result of large numbers of firing neurons, and the different firing rates are reflected in the EEG signal as a combination of oscillations at different frequencies. Even though the raw EEG-signal often has a millisecond temporal resolution the actual features used are often based on the frequency spectrum, calculated for time windows that may be many seconds long. It is common to compare the power within bands of frequencies in such spectra. Standard frequency bands are: delta (1-4 Hz), theta (4-8 Hz), alpha (8-13 Hz), beta (13-30 Hz) and gamma (30-100 Hz). The upper limit of the gamma band can vary and it is often left unspecified, as the high frequencies generally have much lower power.

Using the Emotiv Epoc we implemented a form of adaptive BCI, inspired by previous work on EEG-based classification of working memory (WM) load (Gevins et al., 1998; Smith et al., 2001; Gevins & Smith, 2003; Grimes et al., 2008). Grimes et al. (2008) presented an algorithm for classification of WM load while investigating the effect of many relevant parameters, such as the need for training data, number of electrodes, and levels to distinguish between. They showed that it was possible to get an classification accuracy of up to 99% for two levels, and that accuracy decreased in a controlled fashion as training time, number of electrodes, etc., were reduced. Based on such previous work we were hopeful that we would be able to create a working prototype using an EEG-based adaptive BCI.

### 4.3.1 Realistic cognitive training

To increase the realism and the ecological validity of the training we implemented a more realistic version of a classic cognitive training task, using animated characters in a virtual 3d-environment to increase the realism of both context and primary stimuli. The training task was based on the **n-back** task, commonly used for working memory training (Dahlin et al., 2008; Jaeggi et al., 2008). In a typical implementation of the basic n-back task, the subject is presented with a series of numbers and asked to compare each new number to the one seen n steps before. With n=1 the question is if the new number is the same as the last, with n=2 if it is the same as the number before the last, etc. This requires the subject to remember the n previous numbers and to update this list each time a new number is presented. The numbers can be exchanged for any stimuli, and it is possible to create a dual n-back task, for example, by presenting numbers at different locations, requiring the subject to remember and compare both the position and the number for each new presentation. Such a dual-n-back task can be very demanding and has been shown to improve measures of fluid (that is, general) intelligence (Jaeggi et al., 2008). In our version, the task is to remember which characters have made which movements over the last few steps (figure 4.2, left). The idea is that keeping track of what people are doing in a 3d-environment is a lot closer to the type of realistic interaction that humans are most familiar with, especially in an everyday context. Thus this setup should be beneficial for ecological validity, and improve the chance of transfer to cognitive improvements in everyday interactions.

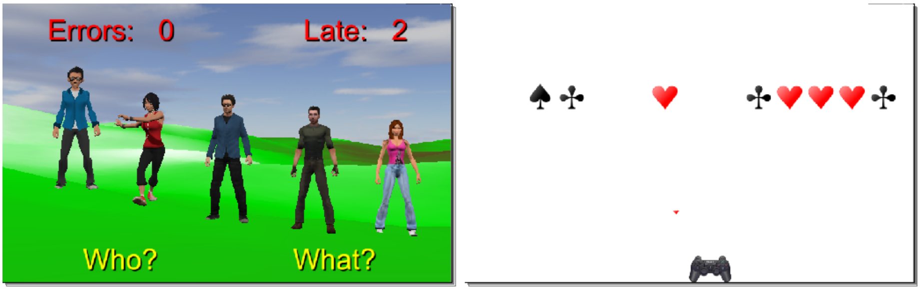

Figure 4.2: The two tasks implemented to evaluate a RBBCI system targeting cognitive training. Left: realistic version of a dual-n-back task, asking who did what, n steps back. Right: simple implementation of the classic space invaders game. The player (represented by the gamepad) can move left and right and must shoot down all the aliens (card symbols) before they reach the bottom of the screen.

### 4.3.2 Adapting to arousal

The adaptive aspect of this implementation has two parts: what to adapt to and how to adapt. Optimally we would like to be able to adapt to the amount of prediction errors in relevant areas of the brain, tracking synchronization and related presence. However, it is unclear if this is possible using the Emotiv Epoc, so we instead focused on using pattern classification to estimate cognitive states related to prediction errors, based on EEG-features. We chose to use reported arousal as the output class, since arousal is easier to relate to prediction errors than, for example, WM load. In essence, arousal can be related to the basic detection that something is not as it should be, arousing humans to act in order to change the environment to fit the predicted ideal. Arousal has also been shown to have a direct effect on training effects, suggesting that the best effect is attained when level of arousal is somewhere in the middle, not too low or too high (Salehi et al., 2010). This is in sync with the desire for the right amount of prediction errors.

To be able to get information on the users level of arousal we divided the task into blocks of 60 seconds and queried the user about their level of arousal after each block. See paper V for further details on this setup. These blocks were also the level at which we introduced adaptation; that is, the conditions for the task could change from one block to another, based on reported or classified arousal, but not within a single block. Possible adaptations included changing n (the number of items to remember), changing the time between new stimuli, and adding randomness to the motions of the characters. The first two adaptations are traditional parameters of n-back, while the third one was intended to add unpredictability to the stimuli and thereby facilitate synchronization and learning.

Because of difficulties getting this setup to work as intended we also implemented a simple version of the space invaders game (figure 4.2, right), in order

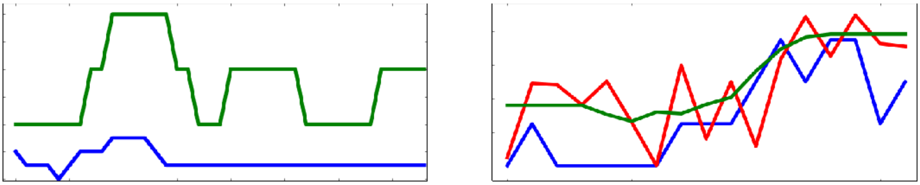

Figure 4.3: Left: Changes in difficulty (n) over time (green) and reported arousal (blue). This illustrates one instance where the subject did not report any change in arousal in spite of changing difficulty, for the latter part of the trial. Right: Reported (blue) and classified (red) arousal for a trial with correlation r=0.6. If the classified arousal is smoothed (green) one can see how it follows the trend in reported arousal.

to further investigate the performance of the EEG-based arousal classification. For this task the only adaptation was the speed at which the "aliens" move and descend.

### 4.3.3 Evaluation

To evaluate the system we set out to gather data from a number of subjects, with several trials per subject. Each trial was about 60 minutes long, including introductions and initial familiarization with the program, etc. For each subject an initial trial was used to gather training data and to evaluate the suitability of the subject, since BCI performance is often highly variable between subjects (Allison & Neuper, 2010). This was followed by four more trials in total, two with increased unpredictability in character movements and two normal trials, in random order. For each pair of trials (with or without increased unpredictability) training data from the first was added to the classifiers used in the second trial. Using this setup we hoped to be able to track how performance in training and classification developed over time, while making it possible to compare data with and without added unpredictability.

Unfortunately, while we managed to get this setup to work to a limited degree for some individuals, we failed to create a system where this method worked reliably across subjects and trials. This was in large part because of problems in getting the desired connection between task parameters and (reported) user arousal, especially for the n-back task (figure 4.3, left). The problem was further aggravated since our adaptive setup was particularly sensitive to such errors, and because of a high degree of noise in the EEG-signal with resulting uncertainty in classification output. Because of these problems data collection was aborted before completed as planned.

The classification performance achieved was not sufficient to support the adaptations we aimed for, but a subset of trials showed a correlation between reported arousal and classified arousal, indicating that systems of this kind, while vulnerable, have the potential to work as intended in optimal conditions.

Differences between the cognitive training task and the space invaders game also suggest a possible role for gaming methods in addressing some of the problems.

The gathered data covers 18 trials over 4 subjects: 13 trials with n-back and 5 trials with space invaders. For each trial we divided the data into two equal parts and used the first half as training data and the second half as test data. To investigate the classification performance we computed the correlation coefficient (r) between reported arousal and classified arousal in the test data, using classifiers based on the training data for the same trial. In total there are 5 trials (28%) with r>=0.6 (see figure 4.3, right, for an example of a trial with r=0.6). This can be broken down into n-back with 23% of 13 trials at r>=0.6, and space invaders with 40% of 5 trials at r>=0.6. These statistics are admittedly low power, but they may reflect increased arousal variation and engagement in the space invaders task.

### 4.3.4 Conclusion

In retrospect our prototype probably tried to do too much at once. For example, the adaptive setup made the application sensitive to variation in the classification performance, and the amount of training data we used was less than in many other BCI applications. This result should not be taken to mean that commercial EEG devices cannot be used for adaptive BCI applications, but perhaps as further warning to take one step at the time.

It is interesting to note that the “space invaders” game task showed better performance than the n-back training task. Although this result is not statistically significant, it does suggest a possibility for future experiments to create functioning RBBCI applications. Presence and your synchronization with any environment depends greatly on your attention to the environment. Game technologies and methods include many ways to capture and direct the user’s attention to the game and to the designed content, that may be valuable in BCI applications (Nijholt et al., 2009; Gürkök et al., 2012).

## Summary

The value of computer applications that combine realistic interaction with an understanding of the human brain is exemplified using computerized cognitive training. In particular, the use of adaptive BCIs that may interpret brain measurements informed by theories of brain function may be used to track presence and similar cognitive states, and adapt computer applications for optimal experience or effect. This combination of realistic interaction (exemplified using VR) and adaptive BCIs is further related to a multidisciplinary context through the concept of reality-based brain-computer interaction (RBBCI).

While we did not get the desired result using our RBBCI prototype application, the case for the value of RBBCI is still valid, and we hope that the approach and the methods described above will be further developed and evaluated in future projects. It is still likely that a combination of realistic interaction and real-time adaptations to cognitive state will be a valuable approach for development of applications for cognitive training, rehabilitation, and diagnostics.

# Chapter 5

# There and back again

My initial interest in VR had much to do with computer graphics in general, and the use of 3d-graphics in computer games. Working with VR was a way to explore the cutting edge of computer graphics and interactive simulation. Since then, over the last 15 years, computer games have developed tremendously to cover both cutting edge technology and a wide range of applications, such as serious gaming and edutainment. The evaluation of the RBBCI prototype application above, and the importance of attention for deciding what is synchronized into the user's subjective mental reality, suggests that returning to a closer look at engaging computer games may be fruitful.

While the concept of presence has been the central focus in only two of the papers presented here it has always been there in my mind, as a concept that is central to how the human brain works in the context of computer-generated realism (as a generalization of VR). Papers I and III discuss and investigate issues that provide valuable background for the reasoning about presence in papers II and IV. A general interpretation of what presence is and of its role in HCI saturates this thesis and underlies the view on presence-related applications presented in chapter 4.

The concept of RBBCI is suggested to summarize the context of computer applications relating to human brains, virtual realities, and computer-generated presence. The essence of RBBCI is that brain function is intimately related to the human perception of reality, and that the use of VR technology allows us to manipulate the computer-generated reality, influencing what is synchronized and thus the associated brain functions of the user. The computer interacts with the brain through the presented reality, and by interpreting brain measurements as resulting from aspects of, and changes in, this reality. Results from the brain imaging studies presented here provide examples of changing brain activity that may contribute to the interpretation of future brain measurements in similar contexts.

Before I arrived at the RBBCI concept I considered describing my research as *immersive brain-computer interaction.* The concept of immersion has several definitions; my initial conception was of a system where the user was immersed in an environment that was in turn (partially) adapted to brain measurements interpreted by the computer. Considering the possible developments towards further use of gaming methods to improve RBBCI applications, however, it may be interesting to further investigate the connection between presence, as described in this thesis, and the concept of immersion as it is used within game development and games user research.

## 5.1 Trails into the future

As suggested above, one possible continuation of the work presented in this thesis is to integrate it properly with research on computer games and serious gaming. The potential of games to grab users' attention, and guide it to specific aspects of a computer-generated reality (game world) can be very valuable. At the same time, a focus on realistic interaction and everyday realism, or integration of tasks shown to work for cognitive training, is still rare in computer games. The work presented in this thesis may provide guidance for the development of games that integrate everyday realism and verified cognitive training tasks with motivating gaming mechanisms.

While our difficulties in getting the RBBCI prototype to work as intended suggests that the use of commercial tools for brain measurements still require a lot of care, I do consider the use of such mass produced tools to be an important goal. If recent interest in head-mounted interaction devices such as the Oculus Rift and Google Glass materializes into common use, such devices may provide a platform for the integration of simple brain measurements, or at least psychophysiological measurements in general.

Finally, the connections to mathematics and information theory provided by the free-energy principle, briefly introduced in chapter 2, may provide mathematical solutions to analyzing the information content of a human-computer interface, in relation to expectations and the subjective mental reality of the user. Such an approach may facilitate an advanced form of user modeling, or an integrated view of HCI systems, where the human-computer border is only one of many borders.

# Bibliography

Allison, B. Z., Leeb, R., Brunner, C., Müller-Putz, G. R., Bauernfeind, G., Kelly, J. W., & Neuper, C. (2012). Toward smarter BCIs: extending BCIs through hybridization and intelligent control. *Journal of Neural Engineering*, 9(1), 013001.

Allison, B. Z. & Neuper, C. (2010). Could anyone use a BCI? In D. S. Tan & A. Nijholt (Eds.), *Brain-Computer Interfaces* (pp. 35–54). London: Springer London.

Baddeley, A. (1992). Working memory. *Science*, 255(5044), 556 –559.

Bar, M. (2007). The proactive brain: using analogies and associations to generate predictions. *Trends in Cognitive Sciences*, 11(7), 280–289.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, 59(1), 617–645.

Baumgartner, T., Speck, D., Wettstein, D., Masnari, O., Beeli, G., & Jäncke, L. (2008). Feeling present in arousing virtual reality worlds: Prefrontal brain regions differentially orchestrate presence experience in adults and children. *Frontiers in Human Neuroscience*, 2. PMID: 18958209 PMCID: PMC2572200.

Biocca, F. (1997). The cyborg's dilemma: embodiment in virtual environments. In *, Second International Conference on Cognitive Technology, 1997. 'Humanizing the Information Age'. Proceedings* (pp. 12–26).: IEEE.

Bouchard, S., Dumoulin, S., Talbot, J., Ledoux, A.-A., Phillips, J., Monthuy-Blanc, J., Labonté-Chartrand, G., Robillard, G., Cantamesse, M., & Renaud, P. (2012). Manipulating subjective realism and its impact on presence: Preliminary results on feasibility and neuroanatomical correlates. *Interacting with Computers*, 24(4), 227–236.

Bouchard, S., Talbot, J., Ledoux, A. A., Phillips, J., Cantamasse, M., & Robillard, G. (2009). The meaning of being there is related to a specific activation in the brain located in the parahypocampus. In *Proceedings at the 12th Annual International Workshop on Presence* Los Angeles (CA).

Bouchard, S., Talbot, J., Ledoux, A.-A., Phillips, J., Cantamesse, M., & Robillard, G. (2010). Presence is just an illusion: using fMRI to locate the brain area responsible to the meaning given to places. *Studies in health technology and informatics*, 154, 193–196. PMID: 20543296.

Chaitin, G. (2006). *Meta Math!: The Quest for Omega.* Vintage.

Christou, G., Law, E. L.-C., Green, W., & Hornbaek, K. (2009). Challenges in evaluating usability and user experience of reality-based interaction. In *Proceedings of the 27th international conference extended abstracts on Human factors in computing systems* (pp. 4811–4814). Boston, MA, USA: ACM.

Clemente, M., Rodríguez, A., Rey, B., Rodríguez, A., Baños, R. M., Botella, C., Alcañiz, M., & Ávila, C. (2011). Analyzing the level of presence while navigating in a virtual environment during an fMRI scan. In D. Hutchison, T. Kanade, J. Kittler, J. M. Kleinberg, F. Mattern, J. C. Mitchell, M. Naor, O. Nierstrasz, C. Pandu Rangan, B. Steffen, M. Sudan, D. Terzopoulos, D. Tygar, M. Y. Vardi, G. Weikum, P. Campos, N. Graham, J. Jorge, N. Nunes, P. Palanque, & M. Winckler (Eds.), *Human-Computer Interaction – INTERACT 2011*, volume 6949 (pp. 475–478). Berlin, Heidelberg: Springer Berlin Heidelberg.

Cohen, M. S., Kosslyn, S. M., Breiter, H. C., DiGirolamo, G. J., Thompson, W. L., Anderson, A. K., Bookheimer, S. Y., Rosen, B. R., & Belliveau, J. W. (1996). Changes in cortical activity during mental rotation a mapping study using functional MRI. *Brain*, 119(1), 89–100.

Craik, K. J. W. (1967). *The Nature of Explanation.* CUP Archive.

Cutrell, E. & Tan, D. S. (2007). BCI for passive input in HCI. In *ACM CHI 2008 Workshop on Brain-Computer Interfaces for HCI and Games.*

Dahlin, E., Neely, A. S., Larsson, A., Backman, L., & Nyberg, L. (2008). Transfer of learning after updating training mediated by the striatum. *Science*, 320(5882), 1510–1512.

Daly, J. J. & Wolpaw, J. R. (2008). Brain-computer interfaces in neurological rehabilitation. *The Lancet Neurology*, 7(11), 1032–1043.

Emotiv Corporate (2011). Emotiv corporate. http://emotiv.com/.

Erickson, K. I., Colcombe, S. J., Wadhwa, R., Bherer, L., Peterson, M. S., Scalf, P. E., Kim, J. S., Alvarado, M., & Kramer, A. F. (2007). Training-induced plasticity in older adults: Effects of training on hemispheric asymmetry. *Neurobiology of Aging*, 28(2), 272–283.

Ericsson, K. A. & Charness, N. (1994). Expert performance: Its structure and acquisition. *American Psychologist*, 49(8), 725–747.

Ericsson, K. A., Prietula, M. J., & Cokely, E. T. (2007). The making of an expert. *Harvard business review*, 85(7/8), 114.

Fairclough, S. H. (2009). Fundamentals of physiological computing. *Interacting with Computers*, 21(1-2), 133–145.

Friston, K. (2003). Learning and inference in the brain. *Neural Networks*, 16(9), 1325–1352.

Friston, K. (2005). A theory of cortical responses. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 360(1456), 815–36. PMID: 15937014.

Friston, K. (2008). Hierarchical models in the brain. *PLoS Computational Biology*, 4(11), e1000211. PMC2570625.

Friston, K. (2009). The free-energy principle: a rough guide to the brain? *Trends in Cognitive Sciences*, 13(7), 293–301.

Friston, K. (2010). The free-energy principle: a unified brain theory? *Nat Rev Neurosci*, 11(2), 127–138.

Friston, K. & Stephan, K. (2007). Free-energy and the brain. *Synthese*, 159(3), 417–458.

Friston, K. J., Frith, C. D., Liddle, P. F., & Frackowiak, R. S. J. (1991). Comparing functional (PET) images: The assessment of significant change. *Journal of Cerebral Blood Flow & Metabolism*, 11(4), 690–699.

Frith, C. D. (2007). The social brain? *Philosophical Transactions of the Royal Society B: Biological Sciences*, 362(1480), 671–678.

Frith, U. & Frith, C. D. (2003). Development and neurophysiology of mentalizing. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 358(1431), 459–473. PMID: 12689373 PMCID: PMC1693139.

Gallese, V. & Lakoff, G. (2005). The brain's concepts: the role of the sensory-motor system in conceptual knowledge. *Cognitive Neuropsychology*, 22(3), 455.

George, D. (2008). *How the brain might work: A hierarchical and tempora model for learning and recognition.* PhD thesis, Stanford University.

Gevins, A. & Smith, M. E. (2003). Neurophysiological measures of cognitive workload during human-computer interaction. *Theoretical Issues in Ergonomics Science*, 4(1), 113–131.

Gevins, A., Smith, M. E., Leong, H., McEvoy, L., Whitfield, S., Du, R., & Rush, G. (1998). Monitoring working memory load during computer-based tasks with EEG pattern recognition methods. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 40, 79–91.

Gibson, J. J. (1983). *The Senses Considered as Perceptual Systems*. Praeger, 1 edition.

Gibson, J. J. (1986). *The Ecological Approach To Visual Perception*. Psychology Press, new ed edition.

Girouard, A. (2009). Adaptive brain-computer interface. In *Proc. CHI 2009 exteded abstracts* (pp. 3097–3100). Boston, MA, USA: ACM Press.

Girouard, A. (2010). *Towards adaptive user interfaces using real time fNIRS*. PhD thesis, TUFTS UNIVERSITY.

Girouard, A., Hirshfield, L. M., Solovey, E., & Jacob, R. J. K. (2008). Using functional near-infrared spectroscopy in HCI: toward evaluation methods and adaptive interfaces.

Girouard, A., Solovey, E. T., & Jacob, R. J. (2013). Designing a passive brain computer interface using real time classification of functional near–infrared spectroscopy. *International Journal of Autonomous and Adaptive Communications Systems*, 6(1), 26–44.

Grimes, D., Tan, D. S., Hudson, S. E., Shenoy, P., & Rao, R. P. N. (2008). Feasibility and pragmatics of classifying working memory load with an electroencephalograph. *Proceeding of the twenty-sixth annual SIGCHI conference on Human factors in computing systems*, (pp. 835–844). ACM ID: 1357187.

Gürkök, H., Nijholt, A., & Poel, M. (2012). Brain-computer interface games: Towards a framework. In M. Herrlich, R. Malaka, & M. Masuch (Eds.), *Entertainment Computing - ICEC 2012*, volume 7522 of *Lecture Notes in Computer Science* (pp. 373–380). Springer Berlin / Heidelberg.

Halverson, C. A. (2002). Activity theory and distributed cognition: Or what does CSCW need to DO with theories? *Computer Supported Cooperative Work (CSCW)*, 11(1), 243–267.

Hawkins, J. (2005). *On Intelligence*. Owl Books.

Haynes, J.-D. & Rees, G. (2006). Decoding mental states from brain activity in humans. *Nature reviews. Neuroscience*, 7(7), 523–34. PMID: 16791142.

Hebert, L. E., Weuve, J., Scherr, P. A., & Evans, D. A. (2013). Alzheimer disease in the united states (2010–2050) estimated using the 2010 census. *Neurology*.

Heeger, D. J. & Ress, D. (2002). What does fMRI tell us about neuronal activity? *Nature Reviews Neuroscience*, 3(2), 142–151.

Hirshfield, L. M., Solovey, E. T., Girouard, A., Kebinger, J., Horn, M., Shaer, O., Zigelbaum, J., & Jacob, R. J. K. (2009a). Using brain measurement to evaluate reality based interactions. In *Proc. CHI 2009 Workshop on Challenges in the Evaluation of Usability and User Experience in Reality Based Interaction*.

Hirshfield, L. M., Solovey, E. T., Girouard, A., Kebinger, J., Jacob, R. J., Sassaroli, A., & Fantini, S. (2009b). Brain measurement for usability testing and adaptive interfaces: an example of uncovering syntactic workload with functional near infrared spectroscopy. In *Proc. CHI 2009* (pp. 2185–2194). Boston, MA, USA: ACM Press.

Holzman, L. (2006). What kind of theory is activity theory? *Theory & Psychology*, 16(1), 5 –11.

Huang, G. (2008). Is this a unified theory of the brain. *New Scientist*, 2658, 30–33.

Jacob, R. J. K., Girouard, A., Hirshfield, L. M., Horn, M. S., Shaer, O., Solovey, E. T., & Zigelbaum, J. (2008). Reality-based interaction: a framework for post-WIMP interfaces. In *Proc. CHI 2008*: ACM Press.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences*, 105(19), 6829–6833.

Johnson-Laird, P. N. (1983). *Mental Models: Towards a Cognitive Science of Language, Inference, and Consciousness.* Harvard University Press.

Jäncke, L. (2009). Virtual reality and the role of the prefrontal cortex in adults and children. *Frontiers in Neuroscience*, 3(1).

Kalpouzos, G., Eriksson, J., Sjölie, D., Molin, J., & Nyberg, L. (2010). Neurocognitive systems related to real-world prospective memory. *PLoS ONE*, 5(10), e13304.

Kaptelinin, V. (1996). Activity theory: implications for human-computer interaction. *Context and consciousness: Activity theory and human-computer interaction*, (pp. 103–116).

Kaptelinin, V., Kuutti, K., & Bannon, L. (1995). Activity theory: Basic concepts and applications. *Human-Computer Interaction*, (pp. 189–201).

Kaptelinin, V. & Nardi, B. A. (2006). *Acting with Technology: Activity Theory and Interaction Design.* MIT Press.

Klingberg, T. (2010). Training and plasticity of working memory. *Trends in Cognitive Sciences*, 14(7), 317–324.

Koechlin, E. & Hyafil, A. (2007). Anterior prefrontal function and the limits of human decision-making. *Science*, 318(5850), 594–598.

Kuutti, K. (1996). Activity theory as a potential framework for human-computer interaction research. In *Context and consciousness: activity theory and human-computer interaction.*

Li, S.-C., Schmiedek, F., Huxhold, O., Röcke, C., Smith, J., & Lindenberger, U. (2008). Working memory plasticity in old age: Practice gain, transfer, and maintenance. *Psychology and Aging*, 23(4), 731–742.

Logothetis, N. K. (2008). What we can do and what we cannot do with fMRI. *Nature*, 453(7197), 869–878.

Lombard, M. & Ditton, T. (1997). At the heart of it all: The concept of presence. *Journal of Computer-Mediated Communication*, 3(2), 0–0.

Loomis, J. M. (1992). Distal attribution and presence. *Presence: Teleoper. Virtual Environ.*, 1(1), 113–119.

Michelon, P., Snyder, A. Z., Buckner, R. L., McAvoy, M., & Zacks, J. M. (2003). Neural correlates of incongruous visual informationAn event-related fMRI study. *NeuroImage*, 19(4), 1612–1626.

Millán, J. d. R., Rupp, R., Müller-Putz, G. R., Murray-Smith, R., Giugliemma, C., Tangermann, M., Vidaurre, C., Cincotti, F., Kübler, A., Leeb, R., Neuper, C., Müller, K.-R., & Mattia, D. (2010). Combining brain–computer interfaces and assistive technologies: state-of-the-art and challenges. *Frontiers in Neuroprosthetics*, 4, 161.

Moriguchi, Y., Ohnishi, T., Lane, R. D., Maeda, M., Mori, T., Nemoto, K., Matsuda, H., & Komaki, G. (2006). Impaired self-awareness and theory of mind: An fMRI study of mentalizing in alexithymia. *NeuroImage*, 32(3), 1472–1482.

Mourao-Miranda, J., Ecker, C., Sato, J. R., & Brammer, M. (2009). Dynamic changes in the mental rotation network revealed by pattern recognition analysis of fMRI data. *Journal of Cognitive Neuroscience*, 21(5), 890–904.

Nardi, B. A. (1996). *Context and consciousness: activity theory and human-computer interaction.* MIT Press.

Nijholt, A., Bos, D. P.-O., & Reuderink, B. (2009). Turning shortcomings into challenges: Brain-computer interfaces for games. *Entertainment Computing*, 1(2), 85–94.

Norman, D. A. (1988). *The Psychology Of Everyday Things.* Basic Books.

Norman, D. A. (1999). Affordance, conventions, and design. *interactions*, 6(3), 38–43.

Olson, I. R., Plotzker, A., & Ezzyat, Y. (2007). The enigmatic temporal pole: a review of findings on social and emotional processing. *Brain*, 130(7), 1718–1731.

Owen, A. M., Hampshire, A., Grahn, J. A., Stenton, R., Dajani, S., Burns, A. S., Howard, R. J., & Ballard, C. G. (2010). Putting brain training to the test. *Nature*, 465(7299), 775–778.

O'Malley, C. & Draper, S. (1992). Representation and interaction: Are mental models all in the mind. In Y. Rogers, A. Rutherford, & P. A. Bibby (Eds.), *Models in the Mind: Theory, Perspective and Application.* (pp. 73–91). Academic Press.

Picard, R. W. (2000). *Affective Computing.* MIT Press.

Plass-Oude Bos, D., Reuderink, B., Laar, B., Gürkök, H., Mühl, C., Poel, M., Nijholt, A., & Heylen, D. (2010). Brain-computer interfacing and games. In D. S. Tan & A. Nijholt (Eds.), *Brain-Computer Interfaces* (pp. 149–178). London: Springer London.

Poel, M., Nijboer, F., van den Broek, E. L., Fairclough, S., & Nijholt, A. (2012). : (pp. 379).: ACM Press.

Postma, A. & Barsalou, L. W. (2009). Spatial working memory and imagery: From eye movements to grounded cognition. *Acta Psychologica*, 132(2), 103–105.

Riva, G. (2009). Is presence a technology issue? some insights from cognitive sciences. *Virtual Reality*, 13(3), 159–169.

Riva, G., Waterworth, J. A., Waterworth, E. L., & Mantovani, F. (2011). From intention to action: The role of presence. *New Ideas in Psychology*, 29(1), 24–37.

Rizzo, A. A., Schultheis, M., Kerns, K. A., & Mateer, C. (2004). Analysis of assets for virtual reality applications in neuropsychology. *Neuropsychological Rehabilitation*, 14(1), 207–239.

Rogers, Y. (2005). New theoretical approaches for human-computer interaction. *Annual Review of Information Science and Technology*, 38(1), 87–143.

Rogers, Y. (2012). HCI theory: Classical, modern, and contemporary. *Synthesis Lectures on Human-Centered Informatics*, 5(2), 1–129.

Rogers, Y., Rutherford, A., & Bibby, P. (1992). *Models in the Mind: Theory, Perspective and Application.* London, United Kingdom: Academic Press.

Salehi, B., Cordero, M. I., & Sandi, C. (2010). Learning under stress: The inverted-u-shape function revisited. *Learning & Memory*, 17(10), 522–530.

Schacter, D. L., Addis, D. R., & Buckner, R. L. (2007). Remembering the past to imagine the future: the prospective brain. *Nat Rev Neurosci*, 8(9), 657–661.

Scherer, R., Proll, M., Allison, B., & Muller-Putz, G. R. (2012). : (pp. 163–164).: IEEE.

Shepard, R. N. & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, 171(3972), 701–703.

Silva, F. (2010). EEG: origin and measurement. In *EEG - fMRI* (pp. 19–38). Springer.

Sjölie, D. (2010). Reality-based brain-computer interaction. In *CHI 2010 Workshop on Brain, Body and Bytes: Psychophysiological User Interaction* Atlanta, Georgia, USA.

Sjölie, D. (2011). *Reality-based brain-computer interaction.* Number 11.05 in Report / UMINF. Umeå University, Department of Computing Science.

Sjölie, D., Bodin, K., Eriksson, J., & Janlert, L.-E. (2009). Using brain imaging to assess interaction in immersive VR. In *Proc. CHI 2009 Workshop on Challenges in the Evaluation of Usability and User Experience in Reality Based Interaction* (pp.$\tilde{2}$3). Boston, MA, USA: ACM.

Slater, M. (2002). Presence and the sixth sense. *Presence: Teleoperators & Virtual Environments*, 11(4), 435–439.

Slater, M. & Steed, A. (2000). A virtual presence counter. *Presence: Teleoperators & Virtual Environments*, 9(5), 413–434.

Smith, M. E., Gevins, A., Brown, H., Karnik, A., & Du, R. (2001). Monitoring task loading with multivariate EEG measures during complex forms of human-computer interaction. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 43(3), 366 –380.

Solovey, E., Lalooses, F., Chauncey, K., Weaver, D., Parasi, M., Scheutz, M., Sassaroli, A., Fantini, S., Schermerhorn, P., Girouard, A., et al. (2011). Sensing cognitive multitasking for a brain-based adaptive user interface. In *Proceedings of the 2011 annual conference on Human factors in computing systems* (pp. 383–392).

Solovey, E., Schermerhorn, P., Scheutz, M., Sassaroli, A., Fantini, S., & Jacob, R. (2012). : (pp. 2193).: ACM Press.

Spiers, H. J. & Maguire, E. A. (2006a). Spontaneous mentalizing during an interactive real world task: An fMRI study. *Neuropsychologia*, 44(10), 1674–1682.

Spiers, H. J. & Maguire, E. A. (2006b). Thoughts, behaviour, and brain dynamics during navigation in the real world. *NeuroImage*, 31(4), 1826–1840.

Suchman, L. A. (1987). *Plans and Situated Actions: The Problem of Human-Machine Communication.* Cambridge University Press.

Tagaris, G. A., Kim, S.-G., Strupp, J. P., Andersen, P., Uğurbil, K., & Georgopoulos, A. P. (1997). Mental rotation studied by functional magnetic resonance imaging at high field (4 tesla): Performance and cortical activation. *Journal of Cognitive Neuroscience*, 9(4), 419–432.

Tan, D. S. & Nijholt, A. (2010). Brain-computer interfaces and human-computer interaction. In *Brain-Computer Interfaces - Applying our Minds to Human-Computer Interaction* (pp. 3–19). Springer.

Wilson, T. D. (2009). Activity theory and information seeking. *Annual Review of Information Science and Technology*, 42(1), 119–161.

Zander, T. O. & Kothe, C. (2011). Towards passive brain–computer interfaces: applying brain–computer interface technology to human–machine systems in general. *Journal of Neural Engineering*, 8(2), 025005.

Zander, T. O., Kothe, C., Jatzev, S., & Gaertner, M. (2010). Enhancing human-computer interaction with input from active and passive brain-computer interfaces. In *Brain-Computer Interfaces - Applying our Minds to Human-Computer Interaction* (pp. 181–199). Springer.

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