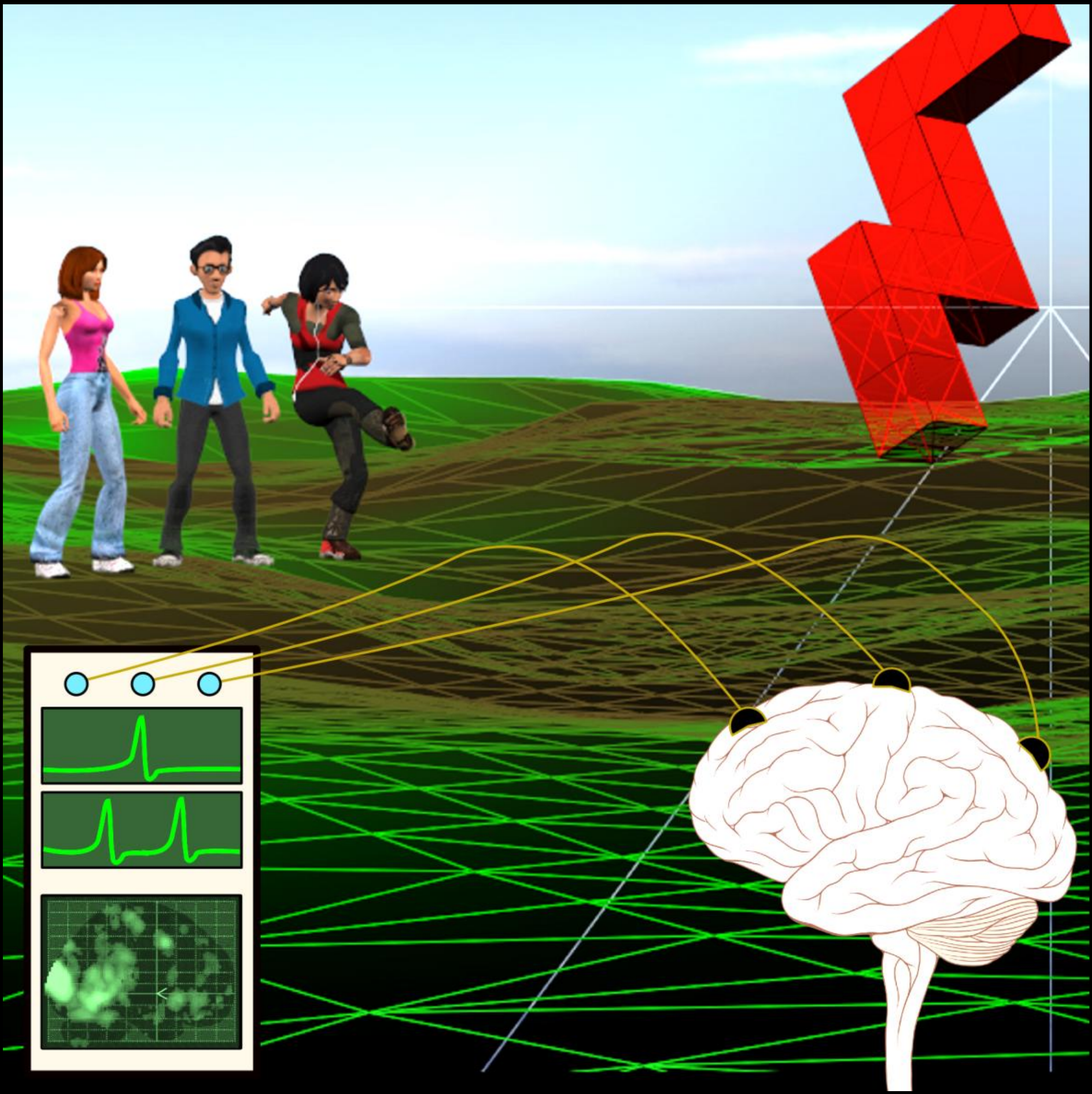

Reality-based brain-computer interaction

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Licentiate thesis, June 2011
Department of Computing Science
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Abstract

Recent developments within human-computer interaction (HCI) and cognitive neuroscience have come together to motivate and enable a framework for HCI with a solid basis in brain function and human reality. Human cognition is increasingly considered to be critically related to the development of human capabilities in the everyday environment (reality). At the same time, increasingly powerful computers continuously make the development of complex applications with realistic interaction easier. Advances in cognitive neuroscience and brain-computer interfaces (BCIs) make it possible to use an understanding of how the brain works in realistic environments to interpret brain measurements and adapt interaction in computer-generated virtual environments (VEs). Adaptive and realistic computer applications have great potential for training, rehabilitation and diagnosis. Realistic interaction environments are important to facilitate transfer to everyday reality and to gain ecological validity. The ability to adapt the interaction is very valuable as any training or learning must be done at the right level in order to optimize the development of skills.

The use of brain measurements as input to computer applications makes it possible to get direct information about how the brain reacts to aspects of a VE. This provides a basis for the development of realistic and adaptive computer applications that target cognitive skills and abilities. Theories of cognition and brain function provide a basis for how such cognitive skills develop, through internalization of interaction with the current environment. By considering how internalization leads to the neural implementation and continuous adaptation of mental simulations in the brain it is possible to relate designed phenomena in a VE to brain measurements.

The work presented in this thesis contributes to a foundation for the development of reality-based brain-computer interaction (RBBCI) applications by combining VR with emerging BCI methods based on an understanding of the human brain in human reality. RBBCI applications can be designed and developed to interact directly with the brain by interpreting brain measurements as responses to deliberate manipulations of a computer-generated reality. As the application adapts to these responses an interaction loop is created that excludes the conscious user. The computer interacts with the brain, through (the virtual) reality.

Sammanfattning

Den senaste tidens utveckling inom människa-dator-interaktion (MDI) och kognitiv neurovetenskap har samverkat till att motivera och möjliggöra ett ramverk för MDI med en stabil grund i hjärnfunktion och människors verklighet. Mänsklig kognition anses till allt högre grad vara kritisk beroende av hur människors förmågor utvecklas i den vardagliga miljön (verkligheten). Samtidigt har ständigt kraftfullare datorer gjort det allt lättare att utveckla komplexa applikationer med realistisk interaktion. Framsteg inom kognitiv neurovetenskap och hjärna-dator-gränssnitt (brain-computer interface, BCI) gör det möjligt att dra nytta av en förståelse av hur hjärnan fungerar i realistiska miljöer för att tolka hjärnmätningar och anpassa interaktion i datorgenererade virtuella miljöer (virtual environment, VE). Adaptiva och realistiska datorapplikationer har stor potential för träning, rehabilitering och diagnostik. Realistiska interaktionsmiljöer är viktiga för att underlätta överföring (transfer) till vardagen och för att nå ekologisk validitet. Möjligheten att anpassa interaktion är mycket värdefull eftersom träning och lärande måste ske på rätt nivå för att optimera effekten.

Genom att använda sig av hjärnmätningar som indata till datorprogram blir det möjligt att få direkt information om hur hjärnan reagerar på olika aspekter av en VE. Detta ger en grund för utveckling av realistiska och adaptiva datorprogram som riktar in sig på kognitiva färdigheter och förmågor. Teorier om kognition och hjärnan ger en bas för att förstå hur sådana kognitiva färdigheter utvecklas genom att interaktion med omgivningen internaliseras. Genom att ta hänsyn till hur internalisering leder till ständig utveckling av mentala simuleringar i hjärnan är det möjligt att relatera designade fenomen i en VE till hjärnmätningar.

Det arbete som presenteras i denna avhandling lägger en grund för utveckling av verklighets-baserad hjärna-dator-interaktions (reality-based brain-computer interaction, RBBCI) applikationer genom att kombinera VR med nya BCI metoder, baserat på en förståelse av den mänskliga hjärnan i människans verklighet. RBBCI-program kan designas och utvecklas för att interagera direkt med hjärnan genom att tolka hjärnmätningar som respons på avsiktliga manipulationer av den datorgenererade verkligheten. När programmet anpassar sig till denna respons uppstår en interaktionsloop som exkluderar den medvetna användaren. Datorn interagerar med hjärnan, genom (den virtuella) verkligheten.

Preface

This thesis consists of a presentation of the foundations for reality-based brain-computer interaction and the following papers.

Paper I: 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”, (CHI 2009 Workshop, 5th April 2009, Boston, USA)

Paper II: 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, ACM Press (2010).

Paper III: Daniel Sjölie. Cognitive Training and the Need for Reality-Based Brain-Computer Interaction: Theoretical Background and Potential Applications. Submitted manuscript.

Paper IV: Daniel Sjölie and Lars-Erik Janlert. Tying activity theory to brain function: theoretical foundations for reality-based brain-computer interaction. Submitted manuscript.

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

1. Daniel Sjölie. The brain and interaction in a multimodal reality. Report UMINF 09.09, Department of Computing Science, Umeå University, 2009.
2. Grégoria Kalpouzos, Johan Eriksson, Daniel Sjölie, Jonas Molin, and Lars Nyberg. Neurocognitive Systems Related to Real-World Prospective Memory. PLoS ONE 5, 10 (2010), e13304.
3. 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).

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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 brain works, and when VRlab got involved in the Swedish Brain Power research program 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 Anne Larsson for help with the equipment and 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 Johanna Pålsson. Even though it may happen 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, June 2011
Daniel Sjölie

Contents

Chapter 1

Introduction

The central theme of this thesis is how an understanding of brain function in realistic environments can provide a foundation for the development of computer applications designed for the human brain. Experience with everyday reality is increasingly recognized as the basis for the development of cognitive skills. Human capabilities have 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 realization drives a development within human-computer interaction (HCI) towards increasingly realistic interaction. This development has recently been summarized using the concept of reality-based interaction (RBI) to understand and compare the many different directions within recent HCI research (Jacob et al., 2008).

The use of realistic interaction is particularly important for applications that relate directly to skills in the real world; i.e., 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). One of the problems with realistic interaction environments in relation to training and rehabilitation is that the complexity of the interaction makes it hard to evaluate in a complete and reliable manner (Christou et al., 2009). Efficient training relies heavily on an ability to guide training to the right level, i.e., corresponding to having a human coach (Ericsson & Charness, 1994). VR applications often have an important advantage when compared to similarly complex training in the real world, as interaction can be controlled and recorded exactly, but this advantage disappears as the task becomes increasingly cognitive in nature. The present work suggests that this shortcoming can be addressed by building on recent developments in brain-computer interfaces (BCIs) in combination with an understanding of brain function in computer-generated realities. This potential use of brain measurements to evaluate interaction in virtual environments (VEs) is introduced in paper I and further developed in papers II and III.

The potential benefits of brain measurements in adaptive and realistic interaction environments, as presented in this thesis, are greatly enhanced by an understanding of brain function in this context. Based on the theoretical foundations presented in this thesis brain measurements can be related to deliberate manipulations of phenomena in a VE. Essentially, theories describe how mental simulations are developed, through internalization of phenomena in the environment, to neural implementations as generative models in the cortical hierarchy. Aspects of the phenomena to be internalized, such as predictability and familiarity, can be directly related to brain function and properties of the corresponding models. Manipulation of such aspects makes it possible to adapt the computer generated reality in order to, e.g., provoke increased brain activity and facilitate detection and diagnosis, or to optimize the development, restoration, or maintenance of cognitive skills through training. The fact that the mental simulations in question are presented as the foundation for cognition on all levels means that 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; e.g., cognitive training, neuropsychiatric rehabilitation or diagnosis of neurodegenerative diseases. These arguments are developed further in chapters 4 and 5, and in (primarily) papers III and IV. The fact that several of these theories can be related to computational neuroscience and brain measurement data analysis makes them particularly interesting when we want to interpret measurements from the brain and feed these into computer applications.

The integration of brain measurements into practical applications has primarily been pursued within the area of brain-computer interfaces (BCIs). The use of such BCIs for adaptive interaction is a recent development within the field (Girouard, 2009; Zander et al., 2010). It is the combination of VR (as a form of RBI) and adaptive BCIs that is captured by the concept of reality-based brain-computer interaction (RBBCI). The RBBCI framework supports development of systems where brain measurements are used to adapt the reality presented to the user and to monitor how the brain reacts to such adaptations, thereby creating systems where the computer can be said to interact directly with the brain rather than with the conscious user. The concept of RBBCI can be used to relate HCI to cognition and theories of brain function, thus facilitating the development of applications that operate in well-designed interaction with the brain. RBBCI is described in further detail in section 7.1 and in paper III.

In order to actually make use of brain measurements with interpretations based on theoretical frameworks these developments must be related to solid results from actual brain studies. Paper II describes a study conducted as part of the present work in order to investigate how brain activity is affected by important aspects of immersive VR. Previous work by others in this area is briefly reviewed in section 4.3 as well as in papers II and III.

In short, the work presented in this thesis is focused on establishing a foundation and investigating the conditions for the development of RBBCI applications, both by investigating brain function in this context using brain imaging, and by integrating related theory. Future work will focus on the development

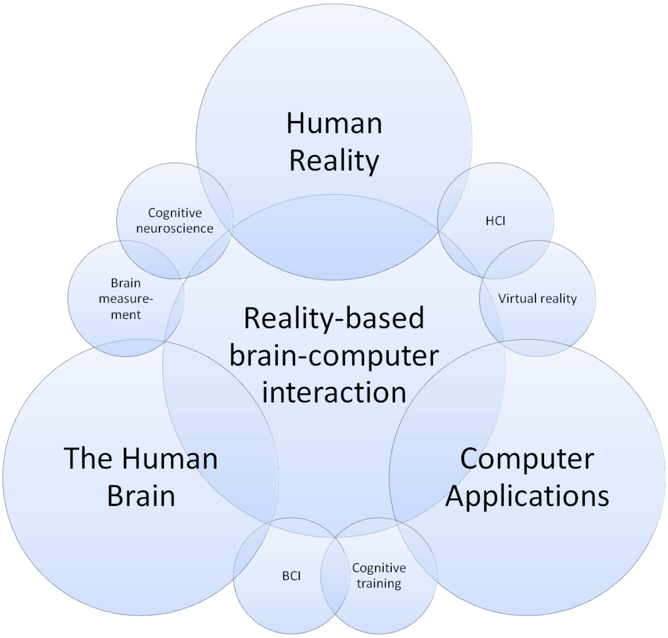

Figure 1.1: Illustration of reality-based brain-computer interaction (RBBCI) in relation to primary influences and related areas. Essentially, RBBCI concerns how *computer applications* can be developed for *the human brain* by consideration of *human reality*. The areas shown should be understood as representative examples of how the primary influences are tied together by previous research and existing methods. It is not a proper Venn diagram.

and evaluation of applications for cognitive training based on this framework.

1.1 Outline

Reality-based brain computer interaction (RBBCI) is a truly interdisciplinary concept. Figure 1.1 illustrates the primary influences and related areas. The following four chapters presents an overview of these areas as the pillars upon which RBBCI rests. Chapters 2 and 3 are oriented towards applications, methods, and related previous work, including examples of what problems RBBCI applications may address and how such applications may be connected to the brain. Chapters 4 and 5 focus more on the theoretical background, describing how the brain can be understood in a realistic interaction environment and how this relates to existing HCI perspectives. In chapter 6 the contributions of the included papers are summarized, followed by a summary of the RBBCI concept in light of the presented foundations and some comments about future work in chapter 7.

Chapter 2

Computer applications for the brain

Establishing a foundation for the further development of computer applications for the brain is the primary goal of the work presented in this thesis. This chapter describes the current state of the art and previous work relating to computer applications that attempt to adapt to and target cognitive skills and the brain. The rest of this thesis essentially describes how such applications can be taken to the next level by combining a direct connection to the brain with an understanding of brain activity in realistic environments.

Virtual reality (VR) techniques have been used for several decades to develop computer applications that target the brain, and the value of realistic VR interaction has been a key motivation for the present work from the start. Computer aided cognitive training has become a popular research area more recently. The real potential of such applications is still unclear but the possibilities warrant further investigation. Cognitive training is also tightly related to applications for diagnostics and cognitive rehabilitation given the inherent connection to development and maintenance of cognitive functions and skills in general. Finally, adaptive psychophysiological computing is presented as an introduction to the increasing popularity of adaptive computer applications based on psychophysiological measurements, with illustrative examples of important previous work.

2.1 Virtual reality

The quest for realistic interaction with computers is arguably most prominent within the field of virtual reality (VR). The reproduction of an interactive experience in a computer-generated world that is as close as possible to a real world experience is an inherent goal of any VR-application. 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”. To reach this goal a combination of advanced computer

Figure 2.1: 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 in six degrees of freedom so that the user can look around freely by moving the head, e.g., to look under the table. This image is from an earlier VR-project in our lab.

graphics and natural interaction devices such as motion-trackers are employed. A representative example is the use of motion-tracked head-mounted displays (HMDs) coupled with computer-generated 3d-environments (figure 2.1). In this case images of the virtual 3d-environment are displayed directly in front of the users eyes and these 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 to both 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).

The motivation for this drive towards realism is often formulated in terms of **ecological validity** and directly related to the potential for transfer. In this context an “ecology” should be understood as an environment, and ecological validity concerns transfer between different environments/ecologies. 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 (i.e., 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. Improved performance in VR training should transfer to the real world and lead to improvements in everyday life.

The primary areas for VR applications today are rehabilitation and training for real world applications; areas where transfer to the real world is of critical importance. VR is of particular interest when training in the real world is expensive and/or dangerous, as with flight simulators or surgery training. It may also be desirable to train on situations that are not controllable in the real world, such as a riot or a large building fire. In general, the ability to have complete control over events in the virtual reality is very valuable and constitutes a distinct advantage with VR that cannot be achieved by other means. These advantages have been reviewed extensively in relation to **virtual rehabilitation**. In addition to general reviews of VR for rehabilitation (Schultheis & Rizzo, 2001) other reviews focus on cognitive rehabilitation (Pugnetti et al., 1995; Rizzo et al., 2001), motor rehabilitation (Sisto et al., 2002) and neuropsychological applications (Rizzo et al., 2004). There is even a structured SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis (Rizzo & Kim, 2005) of the use of VR for rehabilitation and therapy.

The obvious way to achieve high ecological validity is to replicate reality perfectly but even though virtual environments are becoming increasingly realistic, perfection cannot be expected. Thus, it is important to understand which aspects of an interaction environment are most important for transfer to reality. This requires an understanding of the composition of human activities in realistic settings and, in the context of this thesis, how such complex activities and environments can be understood in relation to the brain. These issues are addressed (from different angles) in chapters 4 and 5, and in papers II, III and IV. In this chapter some examples from VR research are described below to illustrate previously shown effects.

One of the most successful applications of VR is to train surgeons in laparoscopic and flexible endoscopic skills, i.e., keyhole surgery. In a recent review Seymour establishes the basic potential for such VR training to transfer to the operating room (Seymour, 2007), remarking that much of the effectiveness of these training applications may be tied to their integration into a curriculum with very deliberate training. An earlier study comparing VR training to video training for surgery shows that VR training is more efficient even though users preferred the video training (Hamilton et al., 2002). The potential for exact control and evaluation of the user's performance was suggested as an important factor here. Another remark in the review by Seymour, also found in many other studies on VR training, is that the results from VR training are better than less realistic variants but not as good as training in the real world. Learning to navigate a real building using either pictures and descriptions, a virtual environment, or the real building, is a clear example of this (Witmer, 1996). As expected, training with VR was better than training with pictures, but not quite as good as training in the real world.

It is worth noting at this point that these virtual environments really do differ greatly from a completely realistic environment. E.g., the navigation training above did not allow for any interactive manipulation with the environment. Similarly, a virtual shop used to train students with severe learning difficulties in the everyday task of shopping was shown to be effective even though the VE was very simple (two straight aisles) compared to the real shop used for evaluation of transfer (Cromby et al., 1996). This illustrates the general potential for transfer from a moderately realistic setting given that the important aspects have been captured. However, if critical components of the task are not captured realism in other aspects may be insufficient. In one of few reported failures to get any transfer from VR to a similar real task, the task had a very strong motor component (pick and place) (Kozak et al., 1993). Such a task can be expected to be highly automatized and rely on low level sensorimotor similarities, e.g., according to activity theory (see section 5.2). Since such aspects as grasping and the weight of objects are indeed different in the VR environment the failure to get transfer to the real world here is not surprising. In order to successfully use VR for cognitive training applications a solid understanding of how human cognition is related to activities and tasks in real and virtual environments is important. This argument is developed in chapters 4 and 5 as well as in papers III and IV, including suggested theoretical foundations for improving such understanding.

An additional advantage of VR-technology is the potential to engage and capture the interest of the user. Simply put, most of the standard tasks used for, e.g., cognitive training or rehabilitation are boring. Presenting the user with a richer environment and more engaging tasks can help the user to maintain focus on the task at hand and to actually maintain the desired amount and intensity of training over time. In this regard there is an overlap between VR and the area of serious gaming (Stone, 2005). Virtual reality is explicit about the value of realism and ecological validity but some experiences from game research can be readily integrated into VR-applications for training or rehabilitation. Research on the impact of parameters such as the difficulty of a task and the feedback presented are examples of game-related results that can be used to optimize training.

2.1.1 The sense of 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 directly related to the subjective experience of a virtual environment as believable, realistic and engaging (Slater, 2002). Presence is of particular interest when considering training and rehabilitation of cognitive abilities since presence is 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 and/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. Understanding something means that one knows how to interact with it, what actions one could take and what the result would 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, e.g., how to look at it and how to reach for it (Postma & Barsalou, 2009). These are actions with quite 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). These ideas are further developed in chapters 4 and 5.

When presence is described in terms of selection of a hypothesis the concept of **breaks in presence** is critically important. Essentially, the argument is that the sense of presence in any environment depends largely on an absence of events that will "break the illusion" (Slater, 2002). Once a hypothesis about being in a certain environment or situation is accepted the brain allows for a range of events that can be considered to match expectations in this context. The high-level hypothesis that one knows where one is and what the current rules are, is afforded a certain preference, encouraging the brain to explain away minor deviations from the expected. It is the truly unexpected events, the ones that cannot be explained without reevaluating the hypothesis about the current situation, that constitute breaks in presence and destroy the sense of being in a real place. For instance, seeing a man in knights armor in the street of a modern city is strange but it can be explained away with a costume party and the general hypothesis about the situation remains unchallenged. If, on the other hand, an open doorway suddenly appears in the middle of the street through which one can see an unfamiliar laboratory the situation may be more dire. This balance between higher-level hypotheses in a constant tug of war with new experiences plays a central role in a family of theories about brain function that is presented further in chapter 4.

Examples of the importance and potential impact of presence in virtual environments can be found in applications of VR to reduce and manage pain. In one influential study Hoffman et al. (2004b) used of VR to distract a single burn victim from the pain. The results show, both that the experienced intensity and the unpleasantness of the pain was reduced, and that less time was spent thinking about the experienced pain. The virtual environment was specifically designed to distract from the burns by making it into a "SnowWorld" where the user travels through an icy canyon while throwing snowballs at passing objects. It is not clear what the significance of the conceptual incongruence between the burning pain sensation and presence within a freezing cold virtual reality is, as the focus of the study is on the general distracting properties of VR. The subjective experience of pain requires attention. Thus, the general potential of immersive VR to engage attention, and divert it from the real world, is a key value. The initial study was followed by closer examination of the experience of presence in the “SnowWorld” and of the neural correlates of VR pain management using fMRI (Hoffman et al., 2003, 2004a, 2006). The neural correlates presented in the later studies clearly show the effects of immersive VR in brain activity in areas commonly related to pain. Pain activation in these areas was confirmed with fMRI and laboratory thermal pain, resulting in five areas of interest. The comparison of activation in these areas with and without VR distraction showed significant reduction of brain activity in all these areas. In other studies the use of VR for pain management has been used to distract children during intravenous placement (needle insertion) (Gold et al., 2006) and cold pressor pain (Dahlquist et al., 2008). The first of these studies show a clear improvement of subjective experience with VR (a fourfold decrease of affective pain) while the second study deals with the additional gain of using a head-mounted display and presents results suggesting that this is effective for some children, but not all.

2.2 Cognitive training

Computer aided cognitive training is based on the idea that it is possible to improve cognitive performance by practicing on certain tasks, implemented in computer applications. 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**, i.e., the potential for improvements on a trained task to carry over to improvements on other 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, i.e., 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, i.e., 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. See paper III for further details.

In a recent 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 between their neural correlates. This directly motivates the use of realistic interaction when developing computer applications for cognitive training and illustrates the need to train the right thing and to create interactive systems with high ecological validity. Reality-based interaction (RBI) in general and virtual reality (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). Another possible reason for the lack of transfer in the study by Owen et al. is that the amount or intensity of the training might simply have been insufficient. This possibility is discussed further in paper III.

A powerful argument for the critical importance of both the amount and the intensity of training can be found in research into the nature of 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. Paper III contains some examples of how coached cognitive training has been shown to be effective. The importance of coaching and support for training and learning is also prominent in descriptions of the zone of proximal development (ZPD) (Cole, 1985; Kaptelinin & Nardi, 2006). This concept is tightly related to the theoretical framework of activity theory and it is treated further in section 5.2 and in paper IV.

Motivating the need for a combination of realistic interaction (VR) and adaptive applications for cognitive training is one of the contributions of the work presented here. Paper III in particular relates cognitive training to the need for realism and adaptivity, establishing a foundation for the concept of reality-based brain-computer interaction (RBBCI) related to theories for cognition and brain function in this context.

2.3 Adaptive psychophysiological computing

As mentioned above, the level of training has been shown to be critically important for effective learning (Ericsson & Charness, 1994; Ericsson et al., 2007). When training on motor tasks or simple cognitive tasks in VR, finding this level

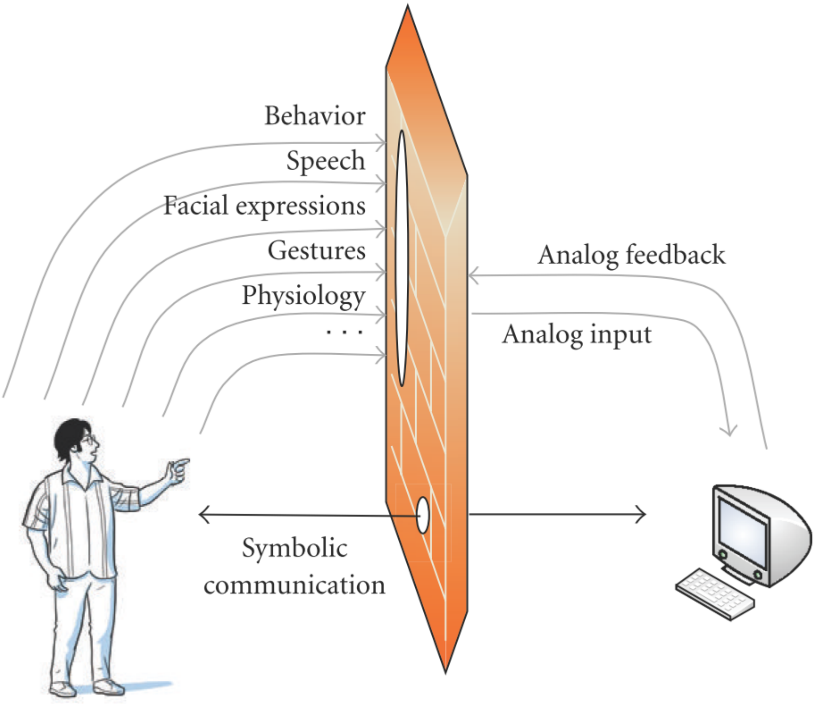

Figure 2.2: In the normal case the computer lacks access to most of the communication channels that humans depend upon in everyday life. All communication must be symbolic. The use of subliminal feedback based on direct psychophysiological measurements allows for the addition of analog input and feedback channels. Reproduced from Walter (2010), with permission.

may be relatively simple since it is (relatively) easy to measure and evaluate the current performance of the user. However, when the interaction becomes more realistic and complex, at the same time as it becomes more internal and cognitive, it becomes much harder to determine how aspects of the interaction environment are related to performance. This problem is treated further in relation to recent HCI developments in section 5.1 and in paper I. In this section adaptive psychophysiological computing is introduced as a promising method for addressing the issue.

A rising interest in adaptive psychophysiological computing can be seen in the HCI community as measurements from the brain or body, i.e., physiological measurements, are increasingly employed as extra input channels for computer applications (Fairclough, 2009; Tan & Nijholt, 2010b). In particular, these measurements can be related to the psychological state (thus the term psycho-physiological computing) of the user and used to adapt the behavior of the application to psychological states such as frustration, overload, or excitement (Picard, 2000; Daly & Wolpaw, 2008; Tan & Nijholt, 2010b; 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 brain-computer interfaces (BCIs) to enable the user to consciously control an application. Common usages of BCIs are further described in section 3.2. 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) but such applications are still rare and the space of possible adaptations is relatively unexplored.

One interesting approach to adaptation was recently demonstrated in a study where subliminal feedback was used to change the interface or the environment of the user depending on galvanic skin response (GSR) measurements, a popular psychophysiological measurement (Walter, 2010). This study renounces the traditional use of psychophysiological signals, where signals are first classified into predetermined symbols that in turn can be used to control the application. Instead signals were used as additional analog input channels and an evolutionary method was used to select between randomly generated variations in the interaction environment based on analog GSR readings (see figure 2.2). In this way such factors as background color, text size and ambient room lighting were subliminally adapted in small steps that were not noticed by the user. Thus, these adaptations were made completely without conscious interaction with the user. The interaction environment resulting from a series of such adaptations was shown to lead to significantly improved performance in the investigated tasks, making such methods very interesting in the context of cognitive training in VR environments. The potential for subliminal adaptations in such environments is indeed great and the level of performance is of prime interest for cognitive training applications.

Adaptive psychophysiological computing has recently been integrated with VR technology to adapt systems for motor rehabilitation based on the user's emotions (Mihelj et al., 2009). In another application cognitive rehabilitation using VR was combined with automatic adjustment of, e.g., the difficulty level of tasks depending on performance (Tost et al., 2009). The development of such systems demonstrates the increasing feasibility of using measurements from brain and body to adapt virtual environments. Still, the use of brain measurements in such systems is uncommon and further development can benefit from considerations of recent theoretical developments in HCI and cognitive neuroscience. Chapters 4 and 5 aim to lay down such a foundation.

Chapter 3

Connecting to the brain

In order to construct systems for interaction with the brain an interface to the brain is required. Brain activity must be measured in some sense. This chapter first introduces brain imaging in general with a focus on the two methods for brain measurements that have been and/or will be used in the present and future work: fMRI and EEG. FMRI has been used in the first studies in this work, described in paper I, paper II and in Kalpouzos et al. (2010). EEG will be used for future developments.

The change from fMRI to EEG reflects a shift in focus from investigation of basic parameters of brain function in VR applications to the development of a foundation for practical applications. The general overview of brain imaging is followed by an account of previous research into practical brain-computer interfaces (BCIs), including typical applications and future potential. The role of BCIs in the context of RBBCI is primarily developed in paper III. In total this chapter should give a good sense of what kind of information it is currently possible to get by connecting to the brain.

3.1 Brain imaging

Brain imaging is the collective term for techniques used to measure and create images of the brain, possibly in action. Different methods can be used to image the structure of the brain or to measure activity in the brain over a time period. The methods used in the work presented here are functional magnetic-resonance imaging (fMRI) and electroencephalography (EEG), two methods for measuring the activity in the brain. These are introduced further in sections below.

Magnetic-resonance imaging (MRI) can also be used to get high resolution static images of the structure of the brain and specific MRI techniques can be used to target different structural features (Deichmann et al., 2010). For instance, diffusion tensor imaging (DTI) can be used to map neural tracts in the brain by exploiting differences in how water moves in different tissues (Hagmann et al., 2003). Such structural information serves as important constraints on any hypothesis about how areas of the brain are connected and about how the brain works in general. See the section below on functional MRI for some additional details on the basics of MRI.

Positron emission tomography (PET) is another imaging method that has frequently been used to study the brain. The basic functioning of PET is based on an ability to detect photons that are produced as a result of positrons being emitted from decaying radioactive material. Based on the position and timing of detected photons it is possible to calculate where they originated, i.e., where the corresponding radioactive material can be found. This is used together with carefully designed radioactive isotopes (tracers) that integrate with different biological functions in the brain, making it possible to track, e.g., how the concentration of neurotransmitters such as dopamine varies in the brain under different conditions (Ito et al., 1998; Bäckman et al., 2000; McNab et al., 2009). This ability to tap directly into biological pathways is a primary advantage with PET, but the use of radioactive tracers means that subjects are exposed to radiation and normally precludes scanning the same subject several times. It also means that the time resolution and scanning duration is limited by the half-time of the tracer. Tracers usually have half-times of a few minutes or hours and the resulting time resolution is limited to similar numbers. For example, acquiring an image based on blood flow may take 90 seconds and an image based on glucose metabolism may take more than 30 minutes.

PET and MRI are similar in that both methods give high resolution images of the entire brain, including subcortical areas deep beneath the surface of the brain. EEG belongs to another family of methods that are based on taking measurements on the surface of the scalp. Another method with this characteristic is magnetoencephalography (MEG). MEG is similar to EEG in that both signals originate in the electrical currents that arise from neural activity in the brain. For MEG, it is the resulting magnetic fields that are measured (Hämäläinen et al., 1993; Silva, 2010). This comes with some advantages, such as a lower sensitivity to distortions from surrounding tissue, but the hardware required makes the method expensive and cumbersome, especially compared to EEG.

From an “applications and handling” perspective functional near-infrared spectroscopy (fNIRS) is a closer match to EEG. FNIRS is based on the different properties of oxygenated and deoxygenated blood for absorbing and reflecting near-infrared light, together with the fact that the skull bone is relatively translucent to this frequency of light (Izzetoglu et al., 2004; Hoshi, 2007). This makes if possible to use a combination of light-diodes and detectors on the scalp to shine light into the brain, measure the reflected light, and relate this to the blood flow and metabolism in brain areas close to the surface of the brain. This connection between measurements, blood flow, metabolism, and the underlying neural activity is also important for fMRI and it is further developed below. FNIRS is primarily of interest because of its ease of use. The spatial and temporal resolutions of fNIRS are not impressive by itself but this may be of secondary importance for applications where ease of use is essential.

3.1.1 Functional MRI

Functional MRI (fMRI) has emerged as an increasingly popular method for investigating brain activity since the early 1990s. The MRI technology behind fMRI has been under development for almost a century but capabilities matching the requirements for fMRI, such as the creation and manipulation of advanced magnetic field gradients, were not commonplace until around 1990. The fundamental principle behind MRI in general is that the magnetic properties of materials can be examined based on how they react to excitation within a magnetic field. Excitation pulses lead to changes in the local magnetic fields of atomic nuclei, changes that depend on the surrounding material. These changes can be detected and used to classify the material at different positions.

The development of fMRI is based on the fact that the magnetic properties of oxygenated and deoxygenated blood are different. This makes it possible to use MRI to get images of the distribution and flow of oxygenated blood in the brain; i.e., hemodynamics. The use of fMRI to investigate brain function is based on the assumed connection between the delivery of oxygen to areas of the brain (via the blood) to the metabolism in the area and thus to the local neural activity. Compared to other methods for investigating brain function fMRI has a number of advantages. As mentioned above, fMRI combines a high spatial resolution with coverage of the whole brain. Alternatives such as EEG, MEG or fNIRS cannot match the spatial resolution of a few millimeters that can be achieved with fMRI, and when it comes to getting functional measurements of sub-cortical brain areas PET is the only real contender. However, requiring healthy subjects to ingest radioactive materials, as in PET, usually requires specific motivations and the relatively high temporal resolution of fMRI (a few seconds) means that fMRI is preferable in most cases. The spatial resolution of fMRI can in theory be pushed to sub-millimeter resolutions but in practice the resolution is limited by decreasing signal-to-noise ratio and increasing acquisition time so that voxels (volume elements) are usually 2-4 millimeters is size (Huettel et al., 2008). This is enough to differentiate between visible structures in the brain such as gyri (ridges in the wrinkled cortex) at about 10 mm.

Even though the advantages of fMRI make a great case for fMRI a few fundamental limitations should be kept in mind. First, even though the temporal resolution is decent compared to the alternatives a few seconds is still a long time in relation to everything that happens in the brain over such a time period. Also, the fundamental hemodynamics measured are relatively slow processes, extending over tens of seconds. This means that even if the time resolution of the actual fMRI measurements were improved there is an underlying slowness in the measured process that cannot be avoided as long as the measurements reflect blood flow and metabolism. Another fundamental limitation is the imperfect understanding of the relation between the hemodynamics of the brain, the neural activity of the corresponding brain areas, and the actual information processing that we would like to make inferences about in the end. See Logothetis (2008) for an overview of the limitations of fMRI.

The actual signal measured is called the blood-oxygen-level dependent (BOLD)

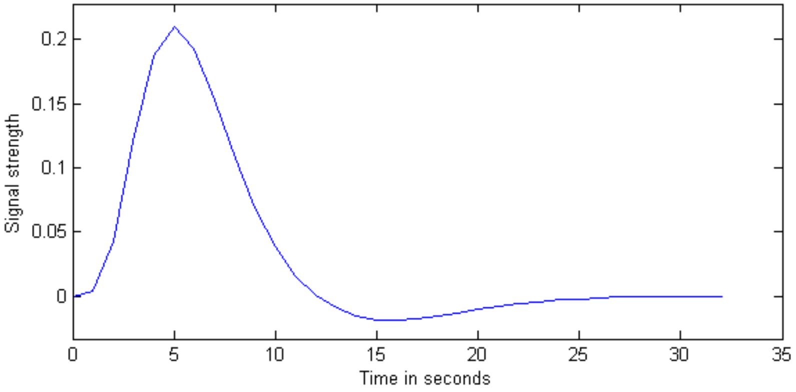

Figure 3.1: The canonical hemodynamic response function (HRF) reflects the nature of the BOLD-signal. This image is generated from the canonical HRF used in the SPM software package, used for analysis of brain imaging data (SPM, 2011). The x-axis is time in seconds and the y-axis is signal strength in arbitrary units (it's the shape that matters).

signal and the relation between neural activity and the BOLD-signal is described by the hemodynamic-response function (HRF). The HRF describes how the hemodynamics (i.e., blood flow) are affected by the metabolic demands related to neuronal activity. In general, the function is described with an initial dip, reflecting the direct consumption of oxygen in the local area, followed by a large increase in the BOLD-signal as the brain overcompensates for the consumed oxygen and a large volume of oxygenated blood arrives (see figure 3.1). This increase generally reaches its max about 5 seconds after the corresponding neural activation and it is followed by a slow decline. It can easily take more than 10 seconds before the BOLD-signal has returned to the level measured before the neural activation. The BOLD-signal does show a certain degree of linear additivity, so that it is possible to tease apart HRFs triggered by events that are less than 10 seconds apart, even though the HRFs overlap. However, such overlap introduces an additional uncertainty, since the nature of this linearity becomes tenuous as the time between events goes down to a few seconds. In many cases separation of events is not even attempted. Instead conclusions are based on the average activation over a longer period of time corresponding to a specific task or condition.

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 of t-values. Such a contrast contains a map of all the voxels in the brain where the magnitude of the difference between two maps has been scaled with the standard deviations. This corresponds to a value for each voxel (position) 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.

A problem concerning statistical inferences based on fMRI data is the large number of measurements gathered and the large number of corresponding statistical tests. In the traditional analysis described above the statistical test is applied to each voxel separately. Since there are a lot of voxels in an fMRI volume this is a large number of tests, several tens of thousands at the least. The usual form of statistical significance testing amounts to asserting that an effect is unlikely to have happened by chance, e.g., by asserting that the probability of getting a certain value by chance is less than 5%. This means that when a large number of tests are made any conclusions made based on a 5% significance threshold would actually be expected to be false in 5% of the cases. This is known as the **multiple comparisons** problem and it might, e.g., lead to erroneously asserting that several thousand brain voxels were significantly more activated in one condition than in another. In order to avoid such false positive results the general approach in fMRI is to simply make the threshold for significance more conservative. There are a number of different methods for estimating which threshold is appropriate but a common P-value for an uncorrected analysis (considered to be liberal in fMRI circuits) is 0.001, corresponding to a 0.1 % probability that the value in a single voxel is due to chance.

One way to alleviate some of the burden of the multiple comparison problem is to consider the spatial dependence among measurements. The reasoning above about expecting 5% false positives is only true if all the tests are independent. In fMRI they are not. There is a considerable amount of spatial dependence in the fMRI data and neighboring voxels normally do have a degree of covariance. This means that the effective number of tests, statistically speaking, is somewhat less. These conditions are exploited using the theory of Gaussian random fields to make calculations concerning expected spatial covariance. It is also common to further reduce the effective number of tests by using spatial smoothing to increase the spatial dependence across the brain voxels.

3.1.2 EEG

Electroencephalography (EEG) is based on measurement of the differences in electrical potential on the scalp that results 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. It is important to note that a large number of neurons must fire together in order to produce a measurable EEG signal. In other words, EEG reflects **synchronous** neural activity in large populations of neurons. This means that changes in EEG signal strength cannot be assumed to correspond directly to changes in the total amount of neural activity. It may very well be a question of an increased or decreased degree of synchronicity in the firing. Traditionally, this unclarity in the relationship between the EEG

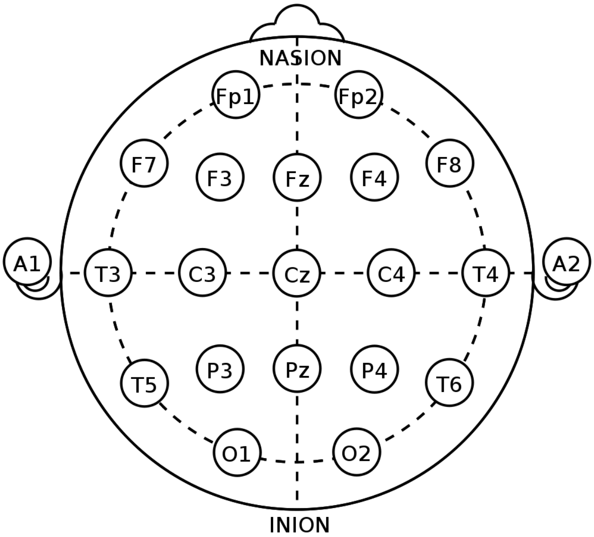

Figure 3.2: The international 10-20 system for electrode placement on the scalp defines a set of standard positions that results can be related to. In this image up is towards the front of the head. Public domain image from Wikimedia Commons (2011a).

signal and neural activity has not been a problem since many correlations have been observed between EEG and psychological state, irrespective of what the underlying neural correlates may be. In such contexts EEG measurements are often described either in terms of how the signal looks when it is plotted and inspected visually (common in clinical applications) or in terms of changing power in predefined frequency bands. For example, the power of the alpha band (8-13 Hz) in the visual cortex increases distinctly when the eyes are closed. Figure 3.3 includes examples of EEG waves.

One of the primary disadvantages of EEG is that the underlying electrical currents can wander around in the brain, making it inherently difficult to determine the location of the source activity. Often positions are given based on the so called “10-20 system” for electrode placements on the scalp (see figure 3.2). This makes it possible to clearly specify how EEG measured at a certain position on the scalp correlates with some psychological or cognitive variable without necessarily knowing what this means in terms of actual brain activity.

Even though EEG often has a millisecond temporal resolution when measured this is usually down-sampled to around 100 Hz since most of the power in the signal is found in lower frequencies. The 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 in general the frequencies close to 100 Hz and upwards have much lower power.

An understanding of EEG in the context of previous fMRI results and theories of brain function is perhaps best supported by the development of neuronal models that aim to explain both fMRI and EEG measurements as resulting from the same underlying neuronal activity. Such models are still in their infancy and details should be expected to change in the future but the overall picture presented has a solid basis in empirical evidence and illustrates how EEG can fit in with other results and theories (Kilner et al., 2005; Kilner & Friston, 2010). In short, the model describes neuronal populations as dynamic systems with neurons that fire at different rates and consume energy in relation to this. FMRI measurements are related to metabolism and thus to the energy consumption while EEG measurements are related to a combination of neuronal spiking frequencies giving a spectral profile where the power varies with the frequency. The key idea is that both the energy consumption and the spectral profile are affected as the dynamics of the systems speeds up or slows down. Thus, an activation measured with fMRI should correspond to a speedup of the neuronal dynamics, and to a corresponding shift in the spectral profile of related EEG measurements towards higher frequencies. In both cases the underlying neuronal phenomenon is that neurons fire more frequently within a given population. In terms of standard EEG measurements this corresponds to a reduced power in the lower frequency bands such as the alpha band and an increase in higher frequency bands such as the gamma band. This is partially supported by results on the relation between EEG, fMRI and working memory load (Michels et al., 2010) but the image is complicated by differences between individuals and brain areas. For example, large individual differences have been demonstrated in studies using EEG to classify working memory load in real time in HCI research (Grimes et al., 2008). One likely factor is the impact of strong couplings between remote brain areas on EEG measurements. More advanced models suggest that oscillations and phase-locking resulting from the influences of one area on another play an important role in the generation of the synchronous activity measured with EEG (David & Friston, 2003).

3.2 Brain-computer interfaces

The idea of using measurements of brain activity to in some way control computer applications has been actively researched for some time in the area of brain-computer interfaces (BCIs). One of the primary motivations for the development of computer interfaces that can bypass the use of ordinary communication channels, such as mouse and keyboard, has been to provide options for patients that are unable to communicate in other ways, e.g., “locked-in” patients (Birbaumer, 2006). The most typical BCI application up until today is probably the “BCI speller”, used to spell out words based on brain measurements. Many of the techniques developed for such spellers are applicable to control of computer applications in general. It makes no difference for the interface if the subject is selecting letters or buttons to control any application.

While fMRI measurements have great advantages for investigating brain function there are many disadvantages when attempting to develop systems for practical use and wide distribution. A few examples have demonstrated that it is possible to use fMRI in real-time to create interactive BCI systems but the high price and cumbersome handling limits the applications to a few well motivated areas. One such area might be using real-time fMRI (rtfMRI) to construct a system where the user is presented with a visualization of the activity in brain areas related to the perception and regulation of pain (deCharms et al., 2005). This feedback was used during training to allow users to see directly what worked as they tried different cognitive strategies for managing pain. After training with rtfMRI feedback it was shown that subjects were able to deliberately manipulate the brain activity in the targeted areas and that this was correlated with perceived pain, even for patients with chronic pain. Other studies have demonstrated the basic potential of rtfMRI using multivariate classification (LaConte et al., 2007) and demonstrating systems where users could successfully balance a pendulum based on real time classification of their measured brain activity (Eklund et al., 2009).

A more affordable and easily handled alternative for real-time brain measurement is fNIRS (Solovey et al., 2009; Hirshfield et al., 2009b). (See section 3.1 above for an introduction to fNIRS). One advantage with fNIRS is that the measurements are of the same kind as fMRI measurements, i.e., they are based on blood flow and neural metabolism, making comparisons to results from the vast fMRI literature relatively straightforward. However, the dominant method of brain measurements for BCI is EEG and recent developments speak to the future potential of this method. The emergence of commercially available and affordable EEG-headsets, such as the Emotiv Epoc (Emotiv Corporate, 2011) (figure 3.3), lowers the threshold for new researchers and developers to integrate BCI features into their systems. This development plays right into the increasing interest for psychophysiological computing among HCI researchers and the desire to tap into the human mind to extend the HCI toolkit (Tan & Nijholt, 2010a). An increasing interest in combining fMRI and EEG, and in developing the relation between these different forms of brain measurement, also speaks to the feasibility of relating theories of brain function to brain measurements and applications utilizing EEG (Mulert & Lemieux, 2010).

BCI spellers implemented using EEG are mostly based either on detection of the P300 or on motor imagery. The P300 is a so called event-related potential (ERP), i.e., a change in the electrical potential measured with EEG that is directly related to an event. In the case of P300, the potential of interest is the positive (hence the P) change in potential measured at the parietal lobule 300 milliseconds after the event (hence the 300). It was in 1965 that Sutton discovered that this potential responded specifically to stimuli that where unexpected or unlikely, as long as they were also task-relevant, i.e., attended (Sutton et al., 1965). Since then this discovery has been extremely useful for the BCI community. A typical implementation of a P300-speller consists of a matrix of letters where rows and columns are flashed randomly. The user is simply asked to pay attention to the letter that he or she wants to select. Since the flashes

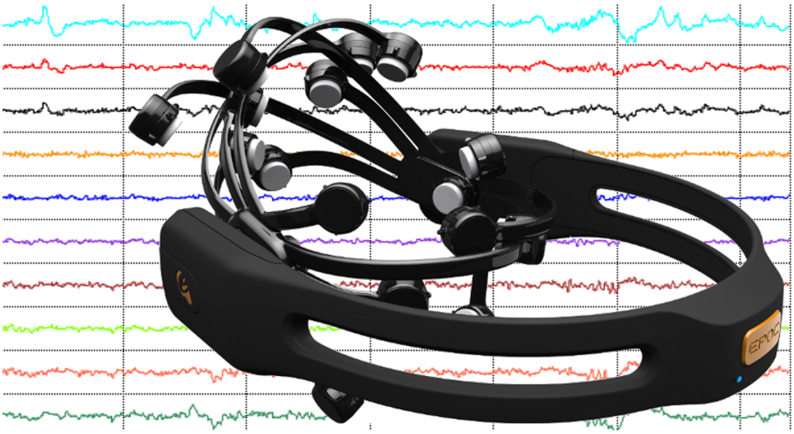

Figure 3.3: In the foreground: the Emotiv Epoc commercial EEG headset. In the background: example EEG signals from the Emotiv Epoc. Image of the headset from Emotiv (Emotiv Corporate, 2011), used with permission.

are randomized they are not expected and when the letter that the user attends flashes this results in a P300 potential that can be detected. Given a sufficient number of flashes of rows and columns it is then possible to match the detected P300 potential to the corresponding rows and columns and figure out which letter was attended. As hinted above this approach can be used to select among any kind of items, for instance real objects on a multi-touch surface (Yuksel et al., 2010).

A corresponding application based on motor imagery instead presents the user with a series of choices where the alternatives correspond to imagery of different motor actions. A simplistic version of this might be the selection of a letter by eliminating half of the remaining letters each time, choosing which group to eliminate by imagining moving either the right or the left hand. Such imagined movements can be detected as changes in the EEG signal near the hand area of the somatosensory cortex in the brain. More specifically, it is normally possible to detect a rhythm in these areas when resting, called the mu rhythm, that disappears with real or imagined movement (Silva, 2010). More advanced applications could accelerate choices by detecting a larger number of different movements and/or detecting combinations of movements, e.g., imagined foot movement of a combination of both hands simultaneously.

In one application with specific relevance for this thesis motor imagery was used with EEG-based BCI to control a car driving on a road in a simple virtual reality (VR) application (Ron-Angevin & Díaz-Estrella, 2008). BCI performance in the VR application was compared to the performance on an equivalent task in a much simpler application. In the VR application the user was presented with feedback in the form of the moving car while the feedback in the alternative application was a simple horizontal bar. Interestingly, they found a significant difference in classification error rates in favor of the VR-application. These results suggest that a rich VR interaction environment may support improved focus in BCI applications, resulting in more easily detected signals.

The P300 paradigm and the use of motor imagery can be taken as prime examples of two different categories of BCI: reactive and active BCI. The P300 potential is always a reaction to some externally presented event while motor imagery requires an active effort to control brain activity by the user. In recent accounts of BCI for use in human-computer interaction these categories have been listed together with a third category: passive BCI (Zander et al., 2010). An application with passive BCI neither relies on specific external events nor requires the user to make a conscious effort to control brain activity. Instead the passive or adaptive BCI is used to adapt or enrich computer applications based on interpretations of the user's current cognitive state (Cutrell & Tan, 2007; Girouard, 2009). Previous work on the classification of working memory (WM) load based on EEG measurements is closely related to this concept. Essentially, it may be desirable to adapt the application, e.g., in terms of the amount or speed of presented information, if it is determined that the WM load is either to high or too low. Grimes et al. recently presented an algorithm for classification of WM load investigating the effect of many relevant parameters such as the need for training data, number of electrodes and levels to distinguish between (Grimes et al., 2008). 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. Experiments with similar ambitions have also been conducted with fNIRS, investigating the mental workload related to different components of tasks and interfaces (Hirshfield et al., 2009b).

Chapter 4

The reality-based brain

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 what brain measurements mean. This chapter attempts to summarize theories and results concerning the function of the brain that constitute a foundation for much of the work presented in this thesis. A description of the brain as an organ developed in its natural environment (reality) is used to introduce some important general ideas such as predictions and mental simulations. This is followed by an account of how recent theories of cognition and brain function relate to this perspective, including explicit claims about implementations in the brain.

Establishing connections between this theoretical foundation and methods that can be used to develop computer applications for the brain (see chapter 2) is an important part of the contributions. The connections to cognitive training and RBBCI are developed in paper III. Further connections to HCI and the framework of activity theory (see section 5.2) are developed in paper IV.

The final section of this chapter briefly reviews previous studies on brain activity in VR environments. The theoretical perspective presented in this chapter must be related to results from such studies in order to secure a grounding that can enable confident use of theoretical reasoning in the development of practical applications. Results from our first study on brain activity in VR, reported in paper II, are included in this account.

4.1 The prospective organ

A basic understanding of the brain may be supported by a consideration of the larger picture. Why do humans have such a large a brain? The human brain is an extraordinarily expensive organ to develop and maintain, and it did not suddenly spring from nowhere. Through the ages it has been popular to view the human mind as qualitatively different from the minds of animals, but modern science suggests that the brain must be explained in terms of gradual

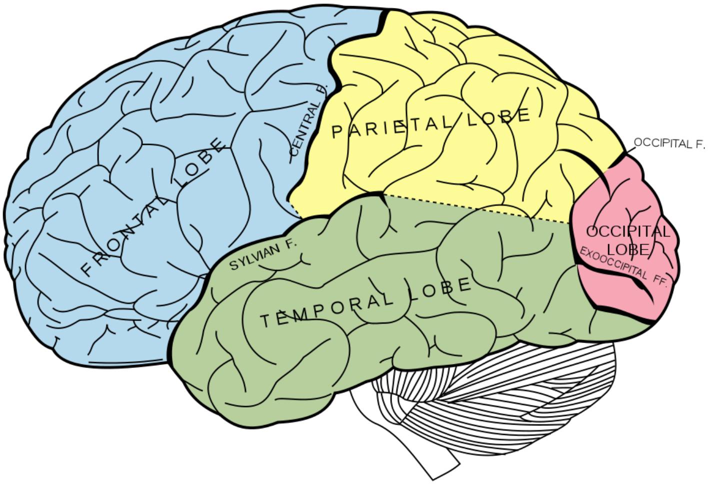

Figure 4.1: The primary division of the human neocortex into lobes. These structures exist in all mammalian brains, but the neocortex in general and the frontal lobe in particular has grown to enormous proportions in the human brain. Public domain image from Wikimedia Commons (2011b).

development and evolution. A brain similar to that of the modern human must have been very useful even before the advent of advanced tool use, language, math, etc, and the basic function of the brain should still be similar to a high degree. This is one of many reasons why several theories of human cognition focus on how “higher” cognitive functions, such as language, are grounded in (i.e., have a foundation in) “lower” brain functions such as perception and action; i.e., the sensory-motor-modalities (Barsalou et al., 2003; Gallese & Lakoff, 2005; Barsalou, 2008).

The structure of the human brain is similar to all mammalian brains in many ways. The neocortex, called so exactly because it has developed relatively recently, covers the older parts of the brain almost completely. The two hemispheres of the brain are structurally very similar and the neocortex is roughly divided into four lobes in each hemisphere (figure 4.1). Primates in general have a larger neocortex than most other mammals (excepting, e.g., dolphins and elephants) and humans in particular have a comparatively huge frontal lobe. This motivates a special focus on the function of the neocortex in any discussion of human cognition. The theories of brain function and cognition presented below relate primarily to the neocortex.

One increasingly popular idea about what the fundamental benefit of the neocortex may be is related to an 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). This is motivated in large part by research into the nature of memory and the similarity in the patterns of neural activation observed when recalling past events and when imagining future events. Remembering the past seems to involve "a constructive process of piecing together bits and pieces", much in the same way as imagining the future seems to work, and there is a substantial overlap in measured brain activity when recalling events from the past and when imagining similar events in the future. Research into mental imagery further suggests that there are important similarities in what the brain does when an action is imagined and when it is actually executed (Shepard & Metzler, 1971; Jeannerod, 1995; Decety & Jeannerod, 1995); and research into so-called mirror neurons adds observation of actions to this group of overlapping brain function as well (Fadiga et al., 1995; Rizzolatti et al., 1996; Gallese & Goldman, 1998; Fogassi et al., 2005). See paper IV for a developed discussion of mirror neurons in this context.

The similarities described above suggest an underlying dynamic representation of events and phenomena that can be employed in the brain to recall, recognize, imagine or act out related scenarios. This idea has recently been captured using the concept on **mental simulations** within the framework of grounded cognition (Barsalou, 2008; Postma & Barsalou, 2009), described as the extension of mental imagery to include unconscious and spontaneous re-enactment of dynamic simulations. Several related theories have employed the idea of mental simulations to explain important aspects of human cognition such as high level concepts (Gallese & Lakoff, 2005; Barsalou et al., 2003) and social cognition (Gallese & Goldman, 1998; Gallese, 2007). An important aspect of this relation between perception, action and cognition in general, is that parts of the mental simulations are actually stored in brain areas related to the corresponding 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. Thus, cognition is described as having a hierarchical structure where concepts and phenomena at higher levels are grounded in lower levels. This view is also supported by the hierarchical structure of the neocortex, discussed further below.

Mental simulations can be directly related to the idea of prediction as a fundamental function of the brain. Running a simulation based on current percepts in the current context essentially corresponds to simulating what might happen next. This basic ability is a feature of the neocortex and it is shared by all mammals. If a dog sees a rabbit run behind a bush it has the ability to predict that the rabbit will probably come out at the other side and intercept it (Sjölander, 1999). I.e., the dog can chase the mental simulation of the future rabbit. Reptiles lack this ability and a snake that loses track of a mouse will not be able to predict what it might do. The behavior of a snake shows no indication of any understanding of how mice work; it simply reacts to the sight or smell of the mouse. This illustrates the basic advantage of the neocortex that has driven its development and supported the success of mammals on earth. The extraordinary success of humans can be related to an ability to represent more complex phenomena and run simulations that can predict possible developments far into the future.

4.2 A unified brain theory?

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, corresponding to mental simulations, may be feasibly implemented in the brain. Several of these theories have mathematical formulations and connections to data analysis and artificial intelligence (AI) that make them particularly interesting in the context of computer applications for 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, e.g., 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. Critically, it is when the input to the brain does not match the expectations that information needs to be sent upwards in the hierarchy. I.e., 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. The key insights here are that:

- the amount or power of such information is directly related to how large the prediction error is, i.e., to how unexpected the input is;
- this ability to focus on new and unexpected information is critically important for cognition and for survival.

The term “free energy”, central to the general mathematical formulations of this reasoning, actually corresponds to an information theoretical measure of surprise, and at the core of the free-energy principle is an assertion that all living organisms must avoid surprises and stay away from surprising states (Friston & Stephan, 2007; Friston, 2009, 2010). The foundations of the free-energy principle as a unified theory for the brain are further developed in paper IV.

Particularly interesting for the subject matter of this thesis is how this framework suggests that the brain essentially contains a model of reality (this is further developed in section 5.3), and that brain activity in large part corresponds to current experiences that are unexpected or surprising; i.e., not correctly predicted. Such poor predictions can be caused either by an incomplete knowledge of the phenomenon, or by fundamental unpredictability. I.e., 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. If the stimuli are fundamentally predictable however, the brain is excellent at detecting and adapting to these stimuli. This basic effect can be recognized in many well-known phenomena, such as repetition suppression, habituation, or odd-ball paradigms, commonly employed as reliable effects in cognitive neuroscience studies. Given the hypothesized correspondence between the experienced reality in general and brain activity similar methods may be employed at a grand scope in virtual reality applications. Many different aspects of the computer-generated reality may be manipulated to be more or less familiar, or more or less predictable, and 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).

4.3 Brain activity and realistic interaction

In order to relate general theories of brain function like those described above to actual brain measurements and practical computer applications a solid basis in relevant studies on brain activity is needed. We have conducted two studies using fMRI to investigate different aspects of brain activity in immersive VR environments. Both studies are described shortly in paper I and results from the first study have been reported in paper II. Results from the second study are partly reported by Kalpouzos et al. (2010) while some additional data-analysis remains as future work.

Brain activity in realistic VR environments has been studied using fMRI several times before. See section 3.1.1 for details on fMRI and Mraz et al. (2003) for a general discussion of the combination of fMRI and VR. In a study by Aguirre et al. (1996) fMRI was used to investigate topographical learning and recall while navigating a simple 3d-maze. Spiers and Maguire (2006; 2007) have extended upon this basic combination of a 3d-environment and fMRI in several important ways. They made sure that the virtual environment (VE) was realistic and full of life by taking advantage of an existing commercial game where the user was able to drive a car in the middle of the busy London traffic. In order to determine the thought process corresponding to a task executed in the VE a verbal report protocol (Ericsson & Simon, 1980) was used in conjunction with a video recording of the subject's viewpoint in the VE. The video was shown to the subject directly following completion of the VE task and the subject was asked to describe verbally what he/she had thought at the times shown on video. It is worth noting that the rich VE probably was very beneficial for the ability to get rich verbal reports afterward. The primary goal of our second fMRI-study was to investigate prospective memory (PM) in a realistic VE (Kalpouzos et al., 2010). We included a verbal report protocol based on a video right after scanning, as Spiers and Maguire. Although the verbal reports contained enough information to tease apart different phases of prospective memory when combined with eye-tracking the amount of reported information was clearly less than in the study by Spiers and Maguire. We suspect that the relative lack of life and movement in our environment is one of the reasons for this. The presence of life in a VE may be very valuable when investigating thought processes in realistic settings.

A complete review of the results from the brain imaging studies mentioned in this section is outside the scope of this overview but a few things should be noted. One general pattern in all these studies is that when they look at the whole brain they show distributed networks of activity. The details of this network vary between studies, possibly because of differences in the task setup, but the hippocampus in particular plays a central role according to most reports. A recent study employing multivariate pattern classification on measurements from the hippocampus constitutes an impressive example of how information can currently be retrieved using brain imaging. Hassabis et al. (2009) were able to decode the position of a subject within a virtual environment based on measurements from the hippocampus even when the visual stimulus for the subject was identical. Subjects were instructed to move around in a virtual room and, after a while, move into a specific corner. The walls of the room were decorated so that the subject could distinguish between the corners when looking around, but for the actual decoding the subject's view was turned down towards the floor. Thus, the subject could only know where he or she was by remembering the position and it was this memory that was successfully decoded. This success means that the decoded spatial information must be treated in the hippocampus and that the neuronal populations involved are relatively large. Differences in small populations would not have been detectable with fMRI.

Another common finding with some relevance for the present subject is brain activity in frontal regions. In the Maguire and Spiers study brain activity in frontal regions was related to route planning or different forms of expectation

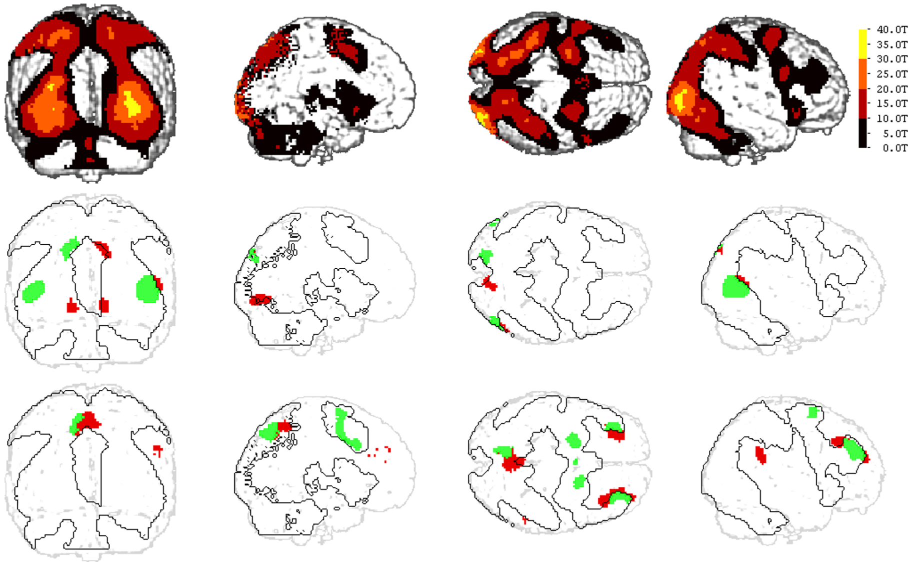

Figure 4.2: Brain areas significantly activated for the mental rotation task in general (top), and areas with increased activity for 3d-motion (middle) and interactivity (bottom). Increased activations are displayed as within (green/bright) or outside (red/dark) of the network (black outline). Images 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 II (Sjölie et al., 2010).

violation (Spiers & Maguire, 2006). The related functions are described in different ways as monitoring uncertain situations, adapting behavior to the environment, or reacting to unexpected events; and they correspond to different areas of the frontal lobe. In the context of the perspectives presented in this chapter all these functions relate to cognitive states where the current hypothesis about the present context is in flux. Lower levels no longer have any higher level goals that provides contexts for predictions. Without context, current experience is unfamiliar, and prediction errors propagate upwards through the hierarchy until they reach the frontal areas of the brain where they need to be resolved. In other words, at moments when there is no clear plan, goal or belief, the mind is more open to external expressions, and prediction errors that correspond to detailed information about the current situation can reach and influence higher-level cognition.

One frontal area of particular interest is the dorsolateral prefrontal cortex (DLPFC). The DLPFC has been identified as a key region in networks related to presence (Jäncke, 2009) and spatial working memory (Constantinidis & Wang, 2004). Spatial working memory has been related to mental imagery and mental simulations (Postma & Barsalou, 2009) by building on such classical results as the speed of mental rotation (Shepard & Metzler, 1971).

Our first fMRI-study, presented in paper II, concerns the effect of certain aspects of a realistic and dynamic interaction environment on brain activity measurements using fMRI. Brain activity was measured while performing a mental rotation task in a virtual environment with varying degrees of motion and interactivity. Our results show that interactivity leads to increased activity in frontal and medial areas while the effect of automatic, easily predicted, motion is restricted to posterior, primarily visual, areas (figure 4.2). These increases are primarily within areas already activated for the general mental rotation task and not (simply) explained by the sensorimotor activity associated with interactivity. Within the perspective given by the theories described above the increased activity from interactivity can be understood as related to an increased unpredictability in the environment. 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.

One clear example of the impact of expectations can be found in a study by Summerfield et al. (2008), examining the relation between repetition suppression and expectations. Repetition suppression refers to the diminishing activation in response to repeated stimuli and influential theories have explained this effect as automatic consequences of the bottom-up flow of perceptual information (Desimone, 1996; Grill-Spector et al., 2006). In the study by Summerfield et al., however, it is shown that the repetition suppression is modulated by the likelihood of a repetition and that the suppression was reduced when the repetition was unexpected. The authors explain this as consistent with a model of top-down predictions combined with bottom-up prediction errors, matching the model described above. In this case the interpretation of the result would be that repetition suppression in general corresponds to a diminished need to trigger prediction errors and that the unexpected repetitions did not match the expectations as well as the expected repetitions and thus triggered more prediction errors, i.e., more activity and a smaller repetition suppression effect.

Chapter 5

Human interaction in reality

This chapter further relates the subject of this thesis to recent HCI research, and to theoretical frameworks currently in use within HCI. The frameworks of reality-based interaction (RBI) and activity theory are introduced briefly and related to the present subject. RBI in particular is directly related to the value of realistic interaction, and previous work concerning evaluation and BCI in connection with RBI is closely related to the work presented in this thesis. The connection between brain function and activity theory is more rare and has been developed at some length in paper IV.

The concept of mental simulations is revisited in a larger context, relating to the view that the brain is essentially running a simulation of reality and the implications of this perspective for the development of RBBCI applications. Finally, the importance of concepts and the use of different terms in different fields is discussed.

5.1 Evaluating reality-based interaction

As the field of HCI advances the interest in more complex and realistic interaction methods grows and the overlap between VR research and HCI research increases. A concept recently introduced in HCI is the framework of reality-based interaction (RBI) that attempts to capture the underlying advantages (and disadvantages) of designing interaction with computers to be similar to interaction with physical reality (Jacob et al., 2008). The framework of RBI relates realistic interaction to human awareness of and skill with the human body, the current environment and social situation as well as a naïve human understanding of physics. These themes are becoming increasingly common in emerging HCI applications, e.g., in the form of tangible interfaces building on naïve human understanding of physics, friction and gravity. 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, when it is formulated as “the ability to act there” and related to existing motor representations (see section 2.1.1). Both effective RBI and presence are strongly related to the familiarity of the current environment.

The concept of RBI and previous work in this area has served as one of the primary inspirations for the direction of the work presented here. In addition to the potential for RBI to serve as a bridge between VR research, HCI and human cognition in realistic environments, previous work on the evaluation of interaction in RBI applications is particularly relevant. The complexity and diversity of RBI applications makes it difficult to establish common practices and accepted measures that would make it possible to compare realistic interaction in many different forms (Christou et al., 2009). One suggested approach is to use brain imaging or passive BCIs to explore how the human brain is affected by different aspects of an RBI application (paper I; Hirshfield et al., 2009a). This approach is highly relevant to the use of passive BCIs to adapt VR applications, suggested in this thesis. The reasoning in chapter 4 about how familiarity and predictability affects brain activity can be used as a basis for interpretation of brain measurements for evaluation and adaptation of RBI applications.

5.2 Activity theory

One theoretical framework with a strong connection to interaction in reality that has gained some popularity within the HCI community is activity theory. This framework is of particular interest in the context of this thesis since it includes strong claims about how cognition and cognitive skills develop through interaction with, and activities within, a complex realistic environment. The connection between activity theory and the perspectives presented in this thesis is further developed in paper IV. The most important points are summarized in this section.

As the name implies, activity is at the very core of the activity theory framework. In fact, the first principle of activity theory is that the human mind (or, as it is often formulated, consciousness) is directly dependent on human activity (Kaptelinin et al., 1995). “You are what you do” and without action, without interaction with the environment, there can be no mind, no consciousness and no cognition. It was the Russian psychologist Lev Vygotsky, generally recognized as the “founding father” of activity theory, that set out to revolutionize psychology in the early 20th century after declaring that there was a “crisis in psychology” and that the dualism prevailing at the time was fundamentally defunct (Kaptelinin & Nardi, 2006). The basic premise is that it simply does not make sense to study the human mind, conceived of as an organ developed in its environment, as separate from this very environment. In order to understand the human mind one must consider it as it interacts with the environment and to understand these interactions the context must be considered, including the social and cultural.

Based on the foundation described above five additional principles have been formulated. These are commonly listed as object-orientedness, internalization/ externalization, mediation, development, and the hierarchical structure of activity (Kaptelinin & Nardi, 2006; Wilson, 2009) and they are tightly interrelated. The discussion below focuses on internalization as a particularly relevant concept in the current context and introduces other concepts as necessary. All these principles are of interest to the subject matter of this thesis. See paper IV for more details.

The object-orientedness of activities is directly related to the dependence on a real-world environment and essentially asserts that human activity must be directed toward the real world and towards some things (objects) that exist, or can come to exist, in the real world. Internalization is the developmental process whereby existing physical objects and processes can become internal and give rise to mental objects representing potential and desirable outcomes of activities in the real world. It is towards these potential outcomes, this vision of an object existing in a certain form, that activities are directed (Leontiev, 1978). Imagining oneself as the winner of an Olympic medal or the owner of a new house are examples of such driving objectives and it is by considering which objects potential components of an activity (e.g., actions) may be oriented towards that it is possible to identify and separate activities.

According to activity theory internalization and externalization should be considered to be ever-present processes that constantly change the balance between the internal and external components of activities. As humans become more familiar with tasks and objects in the real world, these become increasingly internalized, transforming external activities piece by piece into increasingly internal activities and changing the composition of the activity as a whole. The role of automatization in the use of a computer keyboard should be a familiar example of internalization for most readers. When a user first starts using a keyboard great care is needed to locate the keys to press and the activity involves a lot of interaction with the external keyboard such as visually checking that the correct buttons are pressed. As the user becomes proficient with the keyboard, internal (mental) processes can increasingly be used to support interaction with the keyboard and external checking becomes unnecessary. This corresponds closely to interaction based on a mental simulation of (interaction with) the keyboard. The connection between activity theory concepts and mental simulations is one of the primary themes developed in paper IV.

It is important to note that internal activities cannot be understood independently from external activities. While the internal components of human activities can become very rich, filled with internalized objective content that can support complex mental simulations and the full range of human imagination, they will always have some dependence on the external activities of humans and there will always be transformations between the internal and the external, in both directions. Thus, the activity theory view on what internal activity and mental processes covers, i.e., what the brain does, is a very dynamic one with direct connections to the developmental perspective needed for cognitive training or rehabilitation. Together with the importance of mental simulations and their suggested implementations in the brain (see chapter 4) activity theory presents a picture where the critical role of human activities can be followed from development in social and cultural contexts through their role in individual cognition to their neural implementation as generative hierarchical models in the brain.

One particularly well-known concept from activity theory that zeroes in on developmental aspects and the importance of training at the right level is **the zone of proximal development** (ZPD) (Cole, 1985; Kaptelinin & Nardi, 2006). The zone of proximal development was conceived as a way to assess development and learning, particularly in children. Measures of development that were based on current performance failed to predict how a child would develop in the future. Instead, Vygotsky suggests that a measure of the difference between what a child can accomplish on its own and what it can accomplish with the aid of an adult is a far better guide to the developmental potential of the child. It is this difference that has become known as the zone of proximal development. Similar ideas can be used to guide adaptations of computer aided cognitive training by varying the support given and thus probe the developmental potential of the user in the particular context.

5.3 Simulation-based interaction

One of the most helpful concepts from the theories and frameworks presented in chapters 4 and 5 is the concept of mental simulations. In combination with the importance of internalization and the feasibility of dynamic hierarchical models in the brain a picture emerges where the human brain continually runs a simulation of the surrounding environment, trying to match and anticipate the future as well as possible. Such simulations have reached the brain through experience with reality and internalization, based on prediction errors that force refinements of the dynamic models. The (hypothesized) fact that these mental simulations originate in the real environment leads directly to an expectation of similarities between actual reality and the simulation in the brain, both in behavior and in structure. Activity theory is explicit in the claim that cognition is based on internalization of real objects and Daniel Dennett has remarked that for a belief system such as the brain to have survival value the beliefs held must be true, at least to a large degree (Dennett, 1971).

The primary proponent of the free-energy principle, Karl Friston, recently concluded that many theories of brain function can be united under the perspective of “the brain as a generative model of the world it inhabits” (Friston, 2010). 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 reality. Given the hypothesized implementation of this generative model (i.e., simulation) in the brain certain further predictions can be made about the nature of brain measurements relating to changes in the presented reality. Randomness in higher level features should lead to more activity higher up in the hierarchy, e.g., in the frontal lobe, and larger prediction errors, triggered by more unexpected or more unfamiliar events, should also propagate further upwards.

When combined with the idea of internalization and the importance of learning on the right level this framework can be used to carefully fit new phenomena in the virtual environment (VE) into the existing simulation in the brain. Importantly, such new phenomena should be familiar enough to clearly fit in somewhere while at the same time be strange enough to give rise to prediction errors that force the brain simulation to react and change, trying to match and internalize this new phenomenon. This may, for instance, be used to refresh existing simulations related to everyday living by presenting scenarios that are familiar but with some added unpredictability.

5.4 Many names for the things we love

This thesis unavoidably contains a wealth of different terms, concepts and expressions because of its cross-disciplinary nature. Many of these concepts overlap to large or small degrees. Which concept is suitably projected to which and exactly how they are interpreted can depend greatly on the background of the reader and the current perspective. Trying to completely sort this out is beyond the scope of this thesis but the chapters above have attempted to give a few well selected examples of how different concepts can be brought together. Tying concepts together is also one of the primary goals of paper IV. 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 are implemented using prediction models. Activities are more explicitly grounded in the real world but since simulations are based on real 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 have been”, 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 is to be able to predict what might happen and this underlies the perception of something as “real”. To quote Hawkins, “predictability is the very definition of reality” (Hawkins, 2005). It may be clarifying to consider the opposite of reality, i.e., 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: i.e., learning.

Chapter 6

Contributions

This chapter presents a brief summary of each of the papers included in this thesis followed by a short summary of the contributions in total.

6.1 Paper I - Using brain imaging to assess interaction in immersive VR

This paper describes the use of virtual reality (VR) and brain imaging (fMRI) to study and evaluate interaction in VR, as well as the system we used in our studies. Studies conducted using the system are presented briefly to illustrate the potential of the method. Reality-based interaction (RBI) is related to VR, primarily in the shared focus on the importance of relating computer applications to the reality of users. Ecological validity and the basis of the human brain in reality are held forward as two basic motivations for the use of realistic interaction environments. The concepts of presence and breaks in presence are discussed and related to the efficiency of interaction and to evaluation of interaction in realistic environments.

The results from the mental rotation study mentioned in this paper are presented in Paper II (Sjölie et al., 2010) and the results of the study on prospective memory have been published elsewhere (Kalpouzos et al., 2010).

6.2 Paper II - Effects of Interactivity and 3D-motion on Mental Rotation Brain Activity in an Immersive Virtual Environment

The study presented in this paper investigates how brain measurements in an immersive virtual environment are affected by variations in some common aspects of VR applications. This investigation is motivated in relation to the continued development of VR-interaction and the potential use of brain measurements and passive BCI for adaptive VR applications.

Subjects are tasked with a mental rotation task while immersed in a 3d-world using a head-mounted display (HMD) specifically constructed to be compatible with fMRI. The task was to compare a pair of 3d-figures presented inside the 3d-word. Brain activity was compared between three different conditions, all with the same basic mental rotation task. The 3d-figures where either identical or mirrored and they were oriented randomly, necessitating a mental rotation in order to compare them. The difference between the conditions concerned the presence of 3d-motion and the presence of 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.

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 predictability as the pattern of motion was easily explained away at higher levels of the brain and thus did not lead to any further prediction errors. The effect on brain activity of the addition 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 the areas already activated for the mental rotation task in general and areas related to spatial working memory. This result suggests that the addition of interactivity, making the environment less predictable, gave rise to an increase in prediction errors in the areas already recruited for the task.

We particularly point out the value of being able to provoke increased brain activity in task related brain areas, making it possible to, e.g., get enhanced detectability with more interactive and dynamic environments.

6.3 Paper III - Cognitive Training and the Need for Reality-Based Brain-Computer Interaction: Theoretical Background and Potential Applications

This paper presents an overview of the current state of cognitive training research and argues for the need for realistic and adaptive computer applications to meet the challenges in this field. Previous research has shown that cognitive training can lead to improvements and that these can be related to plastic changes in the brain but it remains unclear if it is possible to get general cognitive improvements and transfer to untrained tasks. This unclarity is related to the concepts of near and far transfer. The difficulty of getting far transfer suggests that an increased focus on near transfer and ecological validity is needed. Adaptive psychophysiological computing is introduced as an important tool for adapting the level of training, shown to be of critical importance for effective training, and the use of passive or adaptive brain-computer interfaces is presented as a particularly promising approach. Cognitive training and realistic interaction is further put into a theoretical context, both in relation to research on VR and HCI as well as in relation to theories of brain function such as grounded cognition and the free-energy principle. A short overview of previous results on brain activity in VR is also included. This theoretical background is summarized and brought together with the concept of reality-based brain-computer interaction (RBBCI), presented and motivated in this paper.

Finally, it is illustrated how commercial EEG devices and informed adaptations may be used to construct adaptive and realistic applications for cognitive training, based on RBBCI principles.

6.4 Paper IV - Tying activity theory to brain function: theoretical foundations for reality-based brain-computer interaction

Activity theory has served the HCI community well over the last decades and the underlying theoretical framework contains much that is useful when considering cognition and learning in realistic interaction environments. What is missing though, is a solid connection to brain function and cognition on the individual level. In this paper activity theory is tied to recent theories of cognition and brain function by considering how the concepts within activity theory can be explained and integrated within such new frameworks. The concept of mental simulations and the free-energy principle in particular are used to relate brain function to activity theory. Mental simulations are suggested to correspond to internalized objects or (parts of) internalized activities. The free-energy principle and associated theories are put forward as an explanation of how internalization, externalization and the storage of internalized content is actually implemented in the human brain.

In addition to opening up for the use of activity theory in conjunction with brain-computer interfaces and realistic interaction, tying activity theory to modern theories of brain function can also serve as a catalyst for further development of activity theory concepts. Conflicting interpretations may be compared to other theories with greater ease and foundations such as the free-energy principle may help to resolve conflicts. Activity theory concepts that are not clearly defined, or that are confusing because of an imperfect mapping from the Russian language to English, may be exactly defined by relating them to corresponding implementations in the brain and to mathematical formulations of the models involved. This is particularly valuable in a cross-disciplinary field such as HCI where different researchers and practitioners may be able to relate to different descriptions and formulations.

6.5 Summary

Taken together the papers included in this thesis contribute to:

- introduce the application of brain imaging (fMRI) to evaluation of complex reality-based interaction.
  - Being able to evaluate interaction in complex interaction environments is of key importance for the ability to construct systems that can combine realistic interaction with adaptations to cognitive states.
- investigate the effect of fundamental aspects of interactive VR applications on brain activity using brain imaging.
  - This both serves as support for theoretical reasoning about the framework for such applications and as a foundation for relating results in the vast previous brain imaging literature to brain measurements in these settings.
- establish the need for reality-based brain-computer interaction for cognitive training with solid theoretical motivations.
  - Cognitive training is an area where the development of practical applications is becoming critically important and the problems encountered so far motivate exploration of new, well grounded, approaches.
- relate the theoretical framework of activity theory to brain function.
  - Understanding the components of human activity is critically important when developing applications that aim to support the development and maintenance of human cognitive abilities in the context of such complex human activities.

Thus, all of these papers contribute to the development of a solid foundation for the continued development of computer applications for training, rehabilitation and diagnostics of cognitive abilities; based on the principles of reality-based brain-computer interaction (RBBCI), and grounded in previous results and theoretical frameworks from many related areas of research.

Chapter 7

Conclusion and future work

The key message in this thesis is that human experience in interactive computer-generated realities relates strongly to how the human brain works, how humans perceive reality and to how human cognition develops. This relates directly to the development of cognitive capabilities and applications for cognitive training, rehabilitation, etc. Different methods for measurement of brain activity can be employed to allow the computer to change the generated reality in response to the brain. This allows a training application to adapt the interaction environment and the task to optimize training and, e.g., get the right balance between errors and motivation.

Theories of cognition and brain function have reached a point where they can be employed to support the development of realistic and adaptive computer applications for the brain. In order to develop real applications based on these ideas the existing technologies of virtual reality and adaptive psychophysiological computing (primarily passive BCI) must be combined. The concept of reality-based brain-computer interaction (RBBCI) is suggested as a cornerstone concept to facilitate the development of such applications in cross-disciplinary groups and projects.

Future work will focus on the development and evaluation of RBBCI applications, in particular for cognitive training. Adaptations based on different measurements of mental workload in relation to the familiarity and predictability of the virtual environment will be evaluated. We will also develop the relation between the RBBCI framework and the concept of presence, and the impact of breaks in presence on performance in RBBCI applications.

7.1 Reality-based brain-computer interaction

The concept of reality-based brain-computer interaction (RBBCI) and the related framework is intended to support the development of systems where the computer interacts directly with the brain, based on the principles and techniques described in this thesis. The input to the brain consists of 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 direct 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 by VR in general and by possible adaptations of VR in particular. The primary motivations for considering RBBCI as a unified concept are:

1. Brain measurements and the course of events in the computer-generated reality should be considered together as tightly interrelated through the user's perception of subjective reality.

    - Because cognition and the corresponding brain activity is linked to the user's current subjective reality in a fundamental way with explicit theoretical formulations and practical implications.

2. Cross-disciplinary development of VR applications can benefit greatly from a cornerstone concept such as RBBCI that can be closely tied to all related areas.

    - Because clear communication and sharing of ideas among researchers, developers and practitioners in cross-disciplinary projects is both important and inherently difficult.

3. Applications for cognitive training, rehabilitation, and diagnostics need a combination of realistic interaction and real-time adaptations to cognitive state.

    - Because cognitive training based on specific tasks does not give reliable improvements in general cognitive functioning and because the right level is always essential for optimal effect and sensitivity.

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 and synchronize the computer-generated reality with the associated brain function of the user. Thus, 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.

7.2 Adaptive and realistic cognitive training

The most immediate benefit gained with the perspective presented in this thesis is arguably the possibility to develop adaptations in RBBCI applications that are informed by an understanding of how aspects of a complex realistic task affect brain measurements. The theories presented suggest familiarity and predictability as particularly promising parameters for adjustment. Optimal training should depend on both these parameters being at the right level. Increased familiarity and predictability should work towards reduced brain activity and more unfamiliar or unpredictable stimuli should work towards increased brain activity. An unfamiliar or unpredictable environment and an increased amount of prediction errors can also be expected to lead to brain activity further up in the hierarchy, which generally corresponds to more frontally in the brain. Such manipulations of a virtual environment (VE) should also affect the sense of presence and correspond to an increased number of breaks in presence.

We are currently developing a cognitive training application that will combine a realistic environment with adaptations based on RBBCI principles. The training will be based on the popular n-back task, commonly used for working-memory training. 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. Dahlin et al. (2008) and Jaeggi et al. (2008) are examples of studies where n-back figures prominently. The numbers in this example can be exchanged for any stimuli. In the spatial n-back variation the question is whether the position of some simple stimulus is the same as n steps back. If the stimulus presented at the different positions is also varied it is possible to construct a dual n-back task, where the subject must remember and compare both the position and the identity of the stimulus for each new presentation. This is a very demanding cognitive task and training on a dual spatial n-back test where the second stimulus is presented as sound has been shown to improve measures of fluid (i.e., general) intelligence (Jaeggi et al., 2008).

We have implemented a version of this task transferred to a realistic 3d-environment with animated characters in order to increase the familiarity with the stimuli and the realism of the interaction environment. The task is transformed to remembering which characters have made which movements over the last few steps. The moving character corresponds to the position and the different animations correspond to the second stimulus (see figure 7.1). We also have several more traditional n-back tasks such as images shown on different locations in 3d-space. This allows for a comparison of training with logically identical tasks with stimuli and environments of varying familiarity and realism.

The complexity of the task can be modified in several more or less realistic ways, e.g., by having the characters move around, adjusting the amount of distracting background life in the virtual environment, or by adding unpredictable visual artifacts or noise to break the sense of presence. Varying the realism of the environment and the familiarity of the stimuli is also related to ecological validity and to the difference or “cognitive distance” between tasks. Depending on the target task this also suggests one way to investigate levels between near

Figure 7.1: An implementation of a dual-n-back task for cognitive training in a realistic environment. The stimuli to be remembered are which characters have moved n-steps back and what motions they did.

and far transfer. The application is being implemented using Panda3D (2011), a full-featured 3d game engine, and we have integrated an Emotiv Epoc EEG-headset (Emotiv Corporate, 2011) to make use of brain measurements. We will use this platform to develop applications for cognitive training based on the principles of RBBCI. Future studies will focus on the evaluation of the effectiveness of such applications, and on further investigation of the importance of realism and adaptation.

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