Virtual Reality Technologies for Health and Clinical Applications

Patrice L. (Tamar) Weiss
Emily A. Keshner
Mindy F. Levin *Editors*

Virtual Reality for Physical and Motor Rehabilitation

Springer

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ISBN 978-1-4939-0967-4 ISBN 978-1-4939-0968-1 (eBook)
DOI 10.1007/978-1-4939-0968-1
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2014942842

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

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Chapter 1
Volume Introduction and Overview

Patrice L. (Tamar) Weiss, Emily A. Keshner, and Mindy F. Levin

Objective To introduce the reader to the scope and content of the volume.

The development of technologies that can be applied to rehabilitation offers tremendous promise for enhancing functional capacity by eliminating or minimizing the functional limitations imposed by disability. As new rehabilitation technologies emerge, it is our responsibility as scientists and clinicians to determine how these can best be used to support and modify human behavior. This requires that we understand both how technology development interfaces with human performance and how therapeutic interventions can be adapted to employ the technology effectively. Technologies based on virtual reality (VR) provide multiple levels at which this interface may occur, ranging from the most basic sensorimotor mechanisms to the more complex learning and psychosocial aspects of human behavior.

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P.L. (Tamar) Weiss et al. (eds.), *Virtual Reality for Physical and Motor Rehabilitation*, Virtual Reality Technologies for Health and Clinical Applications,
DOI 10.1007/978-1-4939-0968-1_1, © Springer Science+Business Media New York 2014

This first volume of the Virtual Reality Technologies for Health and Clinical Applications series aims to provide a comprehensive overview of how VR technologies are applied to motor rehabilitation. The first part of this volume identifies the characteristics of VR that affect the mechanisms underlying the motor control processes that support motor relearning. The second part of the volume consists of critical overviews of VR applications that address (1) different therapeutic objectives (e.g., increasing muscle strength, improving sitting balance) and (2) user (client) goals including their relationship to the environment (e.g., participation in work, study, recreation). Chapter authors focus on the latest research findings on the clinical application of VR technology for remediation of motor disorders due to specific physical disabilities (e.g., stroke, traumatic brain injury, Parkinson's syndromes, cerebral palsy, degenerative conditions such as amyotrophic lateral sclerosis and multiple sclerosis). In this first chapter we provide a short summary of each of the subsequent chapters.

Chapter 2 by Katharine L. Cheung, Eugene Tunik, Sergei V. Adamovich, and Lara A. Boyd presents the key aspects of neuroplasticity and how VR technology can capitalize on and influence this phenomenon to promote motor rehabilitation. The nature of neuroplasticity and the physiological mechanisms involved in the induction of both short- and long-term changes in the brain that enable us to store and retrieve motor memories for later use is discussed. The ways in which neuroplastic changes can be classified using the biological principles related to neuroplasticity and the underlying tenets of learning are reviewed. The fundamental elements of experience-dependent neuroplasticity and clinical interventions, including VR technology, which have the potential to induce and affect neuroplasticity are considered. The empirical evidence of the effects of VR on neuroplastic changes in the brain is summarized.

Chapter 3 by Danielle E. Levac and Heidi Sveistrup presents four fundamental variables influencing client motor learning and describe how attributes of VR technologies provide opportunities to target these variables. It summarizes the rationale and evidence for attributes of VR technology that target the motor learning variables of practice, augmented feedback, motivation, and observational learning. The potential for motor learning achieved with VR-based therapy to transfer and generalize to the tasks in the physical environment is discussed. Recommendations are provided for clinicians interested in emphasizing motor learning using VR-based therapy.

Chapter 4 by Robert V. Kenyon and Stephen R. Ellis examines aspects of the technology that are needed to transfer visual information in the physical world to the virtual world by presenting how characteristics of human vision and human perception interface with a virtual environment. The advantages of VR systems for coincident viewing of physical and virtual objects and control of vision are presented. Perception of self-motion and visual perception including vection, vergence, stereovision, size-constancy, and rehabilitation in VR are reviewed.

Chapter 5 by W. Geoffrey Wright, Sarah H. Creem-Regehr, William H. Warren, Eric R. Anson, John Jeka, and Emily A. Keshner deals with the issue of resolving ambiguity between motion of objects in the world and self-motion that reflects interdependence between multimodal signals. A growing body of evidence suggests that visual, vestibular, non-visual, and non-vestibular aspects of virtual world immersion play an important role in perception of self-motion. In this chapter, five experts from the fields of postural and locomotor control present the work they have engaged in to understand how the brain uses multiple pathways of sensory feedback to organize motor behavior. Each discusses their work showing how VR may help us understand or engage the mechanisms underlying sensorimotor integration.

Chapter 6 by Mindy F. Levin, Judith E. Deutsch, Michal Kafri, and Dario G. Liebermann describes the quality of different types of VR environments and their influence on the production of movement. The chapter summarizes the current evidence on the validity of upper and lower limb movements made in different 2D and 3D VR environments. Movement patterns are considered directly as kinematic performance (e.g., endpoint trajectories) and motor quality measures (e.g., joint rotations), or indirectly, as surrogate measures of performance (e.g., heart rate).

Chapter 7 by Alma S. Merians and Gerard G. Fluet describes current clinical evidence for the effectiveness of VR applications on upper limb recovery in individuals who have had a stroke. The chapter summarizes outcomes of upper limb rehabilitation studies using the International Classification of Functioning, Disability, and Health model as a framework and describes motor learning approaches that have been used in VR simulations and interventions for upper limb recovery after stroke. The chapter includes a case study that explores how to effectively use VR/robotic technology for an individualized treatment intervention based on motor learning principles.

Chapter 8 by Anat Mirelman, Judith E. Deutsch, and Jeffrey M. Hausdorff presents a review of VR augmented training for improving walking and reducing fall risk in patients with neurodegenerative disease. It describes the common impairments in gait that are fundamental to neurodegenerative diseases and provides examples from studies on aging, Parkinson's disease and multiple sclerosis. Factors that contribute to problems in mobility are discussed along with current treatment approaches. The review of these topics leads to the rationale and potential advantages of VR-based methods for improving walking and mobility in patients with neurodegenerative disease.

Chapter 9 by Anouk Lamontagne, Emily A. Keshner, Nicoleta Bugnariu, and Joyce Fung reviews how VR can be used to investigate normal and disturbed mechanisms of balance and locomotor control. Loss of upright balance control resulting in falls is a major health problem for older adults and stroke survivors. Balance and mobility deficits arise not only from motor or sensory impairments but also from the inability to select and reweight pertinent sensory information. In particular, the role of the vestibular system and effects of age and stroke on the ability of the central nervous system to resolve sensory conflicts is emphasized, as well as the potential for rehabilitation protocols that include training in virtual environments to improve balance.

Chapter 10 by Dido Green and Peter Wilson provides an overview of the evolution of VR technologies across domains of childhood disability that focuses on the evidence base for applications in research, clinical and community settings in order to optimize outcomes for the child and family. It explores how changing patterns of childhood participation and engagement provide opportunities for using VR technologies for children with disabilities. The International Classification of Functioning, Disability, and Health—Children and Youth version is used as a framework to consider the role of VR technologies in evaluation and intervention across body structures and body function, activity performance and participation across different contexts. Benefits of VR are viewed through the lens of current theory and research to consider broader aspects of the potential impact on brain–behavior relationships.

Chapter 11 by Patrice L. (Tamar) Weiss, Emily A. Keshner, and Mindy F. Levin presents an overview of the evidence for effectiveness of VR for motor rehabilitation and a review of the major technology "breakthroughs" (1986–1995; 1996–2005; 2006–present) that have led to the use of VR for motor rehabilitation. A "Force Field" analysis is presented that looks to the future regarding developments anticipated to occur over the next 5–10 years. Forces that appear to be key factors in helping VR technology have a positive impact on motor rehabilitation have been identified from the information reported in the chapters of this volume, In addition, the forces that currently limit positive progress and, in some cases, prevent advancement towards the goal of effective use of VR technology for motor rehabilitation have been identified.

In conclusion, this volume focuses on the current state-of-the-art in the field of applications of VR for motor rehabilitation. The content has been purposely limited to motor applications in order to critically highlight both the advances that have been made over the past two decades and those that are anticipated in the coming years. At the same time, we recognize the importance of interpreting activity of the motor system within the context of various psychological and cognitive phenomena, as presented in Volume 2 of this series (Psychological and Neurocognitive Interventions edited by Albert A. "Skip" Rizzo and Stéphane Bouchard). We are also aware that technology-based motor rehabilitation must take into account many exciting developments in the world of gaming as presented in Volume 3 of this series (edited by Eva Petersson Brooks and David Brown). Finally, improved motor applications will greatly benefit from the material presented in Volume 4 of this series (Design, Technologies, Tools, Methodologies & Analysis edited by Sue Cobb and Belinda Lange). Thus, to assist the reader, when appropriate, references are made to other chapters in this volume as well as to the three companion volumes in this book series.

Chapter 2
Neuroplasticity and Virtual Reality

Katharine L. Cheung, Eugene Tunik, Sergei V. Adamovich, and Lara A. Boyd

Objective To present the key aspects of neuroplasticity and how VR technology can capitalise on and influence this phenomenon to promote motor rehabilitation.

2.1 Definition of Neuroplasticity

In this chapter we discuss neuroplasticity and consider how VR technology may be used to promote motor learning and rehabilitation. First, we discuss the nature of neuroplasticity and the physiological mechanisms involved in the induction of both short- and long-term changes that enable us to store and retrieve memories for later use. Second, we review how neuroplastic changes can be indexed using biological principles and the underlying tenets of learning. Third, we consider the fundamental

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P.L. (Tamar) Weiss et al. (eds.), *Virtual Reality for Physical and Motor Rehabilitation*, Virtual Reality Technologies for Health and Clinical Applications,
DOI 10.1007/978-1-4939-0968-1_2,

elements of experience-dependent neuroplasticity and clinical interventions that have the potential to induce and affect neuroplasticity. Finally, we consider empirical evidence of the effects of VR on neuroplastic changes in the brain.

The incidence of brain trauma is significant across the globe, and the resultant brain damage of such traumas often carries significant social, economic and human (personal) implications. Fortunately, the brain is highly capable, even beyond its developmental years, to exhibit physiological, functional and structural changes over time; this is likely the substrate for recovery of lost function following an injury (Nudo, 2006). The ability of the nervous system to undergo physiological changes as a result of genetic, behavioural and environmental changes is referred to as neuroplasticity. The processes of development, ageing, learning, memory and neural response to trauma all involve the critical concept of neuroplasticity. (N.B. We will often discuss the concepts of this chapter in terms of the brain following insult or injury—oftentimes it is easier to demonstrate normal brain function by comparing and contrasting with pathological brain states.)

2.1.1 Short-Term Versus Long-Term Changes

Neuroplasticity can occur on multiple levels, meaning the nature and extent of neuroplasticity can vary. Relatively short-term cellular changes can occur as a result of a temporary alteration in excitability of a population of neurons whereas relatively long-term structural changes can occur following long-term practice of a skill or an insult to the brain such as a stroke (Johansen-Berg et al., 2002). For example, short-term neural excitability changes (on the scale of seconds to hours) can be observed by inducing voltage changes in cortical regions of the brain via single-pulsed transcranial magnetic stimulation (TMS); a technique that has been shown to induce only short-term transient effects on the excitability of the brain (Barker, 1999). An example of a longer-term change in the brain can be observed in individuals who have become proficient at certain tasks. For example, empirical evidence of expanded areas of the motor cortex associated with finger movement has been shown in pianists (e.g. Pascual-Leone, Cammarota, Wassermann, Brasil-Neto, Cohen & Hallett, 1993); this is a clear demonstration of how behaviour can result in a long-term physical change in brain regions over time. Long-lasting changes in the brain (on the scale of years to decades) can also be readily observed following insults to the brain such as stroke, which can cause significant tissue damage (Hallet, 2001). Given appropriate rehabilitation however, neuroplastic changes may occur over time that allow for full or partial recovery of any lost function after the insult. Indeed, the neuroplastic nature of the brain allows for it to restructure over time with training and practice. Later in this chapter we discuss ways in which the properties of brain plasticity can be exploited to create long-lasting changes in the brain using technology such as VR.

2.1.2 Changes in Neuronal Traffic

2.1.2.1 Synaptic Pruning and Hebbian Mechanisms

Individual connections between neurons in the brain are continuously being altered depending on environmental and behavioural stimulation and responses to bodily injury. A key component of the theory of neuroplasticity is this dynamic change in neural connectivity, which involves the interplay of two phenomena: synaptic pruning and Hebbian neural interactions. Although synaptic pruning was initially characterised in the visual system (for review, Tessier and Broadie, 2009), pruning can be considered more generally as a genetically programmed reduction in the number of physical synapses between neurons in all sensory–motor systems in the nervous system. This process of pruning is strongly influenced by stimulation from the environment and interactions between neurons during learning—a process termed Hebbian interaction (Hebb, 1949). For example, pairs of neurons that are often excited together will likely exhibit less pruning and perhaps strengthened mutual connectivity, whereas the connections of two neurons that fire independently of one another will become either pruned or weakened. This principle is known colloquially as: "neurons that fire together wire together; neurons that fire apart wire apart" (Bliss & Lomo, 1973). If connections between neurons are no longer being used, their level of connectivity may be reduced or eliminated to allow more room and resources for active connections to be strengthened. Effectively, the connections between neurons are constantly being altered and redefined. An understanding of the principles of synaptic pruning and Hebbian interactions is helpful when considering the design and implementation of technology geared towards altering the connectivity between neurons during the processes of learning and rehabilitation.

2.1.2.2 LTP and LTD Hypothesis of Learning and Memory

While much remains to be elucidated about the nature of learning and memory, the theory of long-term potentiation (LTP) is well documented and a strong candidate as a cellular correlate for learning and memory. LTP is defined as a long-lasting enhancement in signal transmission between neurons that occurs when two neurons are stimulated simultaneously (Bliss & Lomo, 1973); it is one of the ways by which chemical synapses are able to alter in strength. The counterpart of LTP, long-term depression (LTD), occurs when the postsynaptic effects of a given neuron on another are weakened. LTP and LTD are activity-dependent processes that result in an accentuation or a reduction, respectively, in the efficacy of synaptic transmission either through changes in the number of connections between neurons, the modulation of neurotransmitter exchange between neurons, or both (Mulkey & Malenka, 1992).

2.1.3 *Gross Anatomical Changes*

2.1.3.1 Changes in Connectivity

Changes in synaptic dynamics through pruning and Hebbian interactions are evidenced on a macroscopic brain level as connections between different brain regions that are strengthened or weakened over time and by experience. Importantly, the brain has the ability to form new functional connections after it has experienced an injury or perturbation (for review see Calautti & Baron, 2003). Clear evidence of this has been demonstrated in the human motor system. For example, work from Nudo and Milliken (1996) has shown that after a focal stroke in the area of motor cortex responsible for hand function, neurons adjacent to the stroke lesion take over some of the lost motor function. These data and others demonstrate that changes in connectivity within the brain underlie the ability of an individual to recover some of their lost motor function after injury. Despite potential benefits, however, changes in connectivity can also result in pathological consequences. For example, repeated consumption of an addictive substance may result in neural connectivity changes that lead to an increased desire to continue to seek the substance (for review, Alcantra et al., 2011; Thomas, Kalivas, & Shaham, 2008).

2.1.3.2 Changes in Brain Activity Patterns Over Time

There are many current methods that may be used to assess changes in brain activity over time. Although we provide an overview of functional magnetic resonance imaging (fMRI) as an assay tool in more detail below, it is helpful to introduce it here as one way in which global changes in brain activity have been measured. fMRI measures the blood-oxygen-level-dependent (BOLD) signal and, because of its high spatial resolution, is particularly well-suited to investigate whether shifts in brain activity patterns occur over time. Changes in both the location and level of the BOLD signal can reveal evidence of neuroplasticity. Motor learning, for instance, has been shown to change BOLD patterns across distributed brain circuits in both healthy and patient populations. For example, BOLD patterns in different brain regions were examined before and after participants learned a novel motor sequence task (Meehan et al., 2011). Learning the new task changed patterns of brain network activity in both healthy and stroke-damaged brains. Importantly, these data show that individuals after a stroke may compensate by relying on different brain regions than matched healthy controls (e.g. dorsolateral prefrontal cortex instead of dorsal premotor cortex) to support some forms of motor learning (Fig. 2.1).

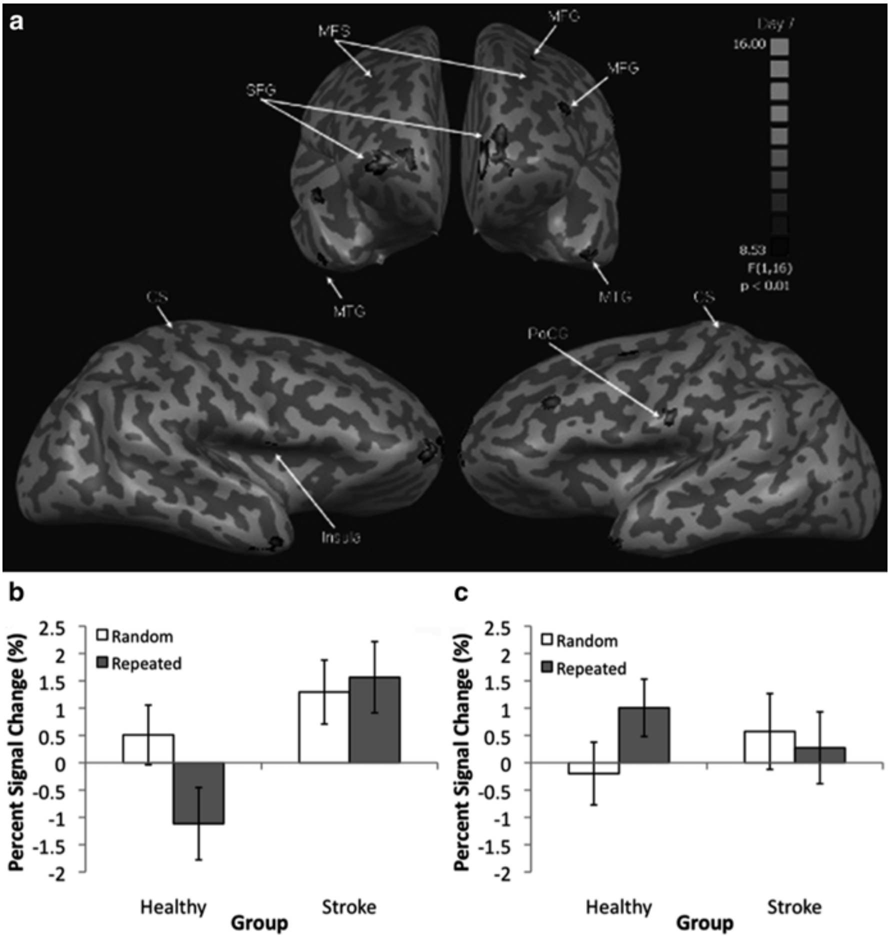

Fig. 2.1 (**a**) Sample fMRI showing the contrast in neural activity between individuals with stroke and matched healthy controls. Importantly, individuals with stroke rely on dorsolateral prefrontal cortex during motor sequence learning (**b**) while matched controls activate the premotor cortex to perform repeated sequences at a delayed retention test (**c**). Adapted from Meehan et al., 2011

2.2 How Can We Index Neuroplasticity?

There are several established methods of measuring neuroplastic changes in the nervous system. Here we discuss methods used to measure changes in excitability of different brain regions, methods to measure changes in metabolic demands in the brain, and methods of evaluating behaviour associated with neural changes.

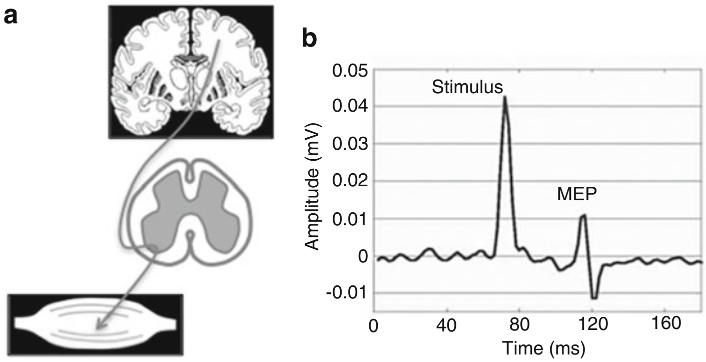

Fig. 2.2 Example of transcranial magnetic stimulation induced motor evoked potential. Stimulation over primary motor cortex induces depolarisation of pyramidal cells (**a**) and leads to an induced muscle response in the periphery (**b**)

2.2.1 Measuring Changes in Excitability of Brain Regions

2.2.1.1 Evoked Potentials

One common method of measuring changes in brain excitability is by presenting a stimulus to the nervous system and recording the electric potential that is evoked. This is called an evoked potential or response (Rothwell, 1997). Signals are typically recorded from the cerebral cortex, brainstem, spinal cord or peripheral nerves. For example, motor-evoked potentials (MEPs) can be recorded by stimulating the motor cortex of a subject and recording the electrical potential evoked in the muscle corresponding to the cortical area being stimulated (Pascual-Leone et al., 2002) (Fig. 2.2). The value of this technique is that differences in cortical excitability associated with disease, recovery or clinical intervention can be examined over time within the same individual. For example, measures of neural excitability could be obtained prior to, and following, a clinical intervention in order to examine the efficacy of the intervention (e.g. the effect of TMS applied to the motor cortex on general cortical excitability). While this technique provides a direct measure of the excitability state of the motor neurons in the brain and spinal cord, it is limited in its ability to assay the excitability of other brain regions, which do not have descending projections to muscles. For assessing more global brain areas, other measures are more appropriate.

2.2.1.2 Electroencephalography (EEG)

Electroencephalography (EEG) is used to measure electrical activity of the brain over time. More specifically, it measures the fluctuation of voltage between different areas in the brain as a result of changes in net ion flow across neuronal membranes during synaptic transmission (Huang et al., 2007). EEG can be used as a diagnostic tool in clinical settings, for example, for the assessment of neural activity during epilepsy, encephalopathies and coma. Although EEG measures electrical activity across the entire surface of the head, the ability to pinpoint the source of the electrical signal using EEG methodology is limited (though more sophisticated source localisation algorithms are emerging (e.g. Koessler et al., 2007)). The main advantage of EEG arises from its outstanding temporal resolution that allows characterisation of changes in brain activity at the millisecond time scale.

2.2.1.3 Magnetoencephalography (MEG)

Magnetoencephalography (MEG) is a technique used to examine magnetic fields produced by electrical currents in the brain. Like EEG, MEG signals are generated by net ion flow throughout neurons in the brain. The advantage of MEG is that it also offers millisecond scale temporal resolution as well as improved spatial resolution over EEG. Some source localisation algorithms show promise in identifying sub-cortical activity in addition to cortical activity (Hämäläinen et al., 1993). These acuity advantages arise because magnetic fields are less susceptible to distortion by the skull and scalp than are the electrical fields measured by EEG. However, MEG is only sensitive to tangential current sources (i.e. those which are parallel to the scalp), allowing it to mainly identify sources coming from depressions in the surface of the brain (sulci) while EEG is sensitive to both radial (directed towards or away from the scalp) and tangential sources (Huang et al., 2007), allowing it to be sensitive to both sulcal sources *and* sources from ridges surrounding the sulci (e.g. gyri). In this regard, MEG and EEG provide supplementary information concerning different parts of the brain and may be used in conjunction with each other to capture multiple physiological processes (Hämäläinen et al., 1993).

2.2.2 Measuring BOLD Contrast and Metabolic Changes

2.2.2.1 Functional Magnetic Resonance Imaging (fMRI)

Functional magnetic resonance imaging (fMRI) is a non-invasive, indirect method of localising and measuring neural activity in the brain based on the relationship between neural activity and the metabolic demands associated with the increased neural activity. As stated earlier in this chapter, most fMRI experiments measure a blood-oxygen-level-dependent (BOLD) response. Changes in the BOLD signal result from changes in the blood deoxyhaemoglobin level in the brain. An increase in neuronal activity results in an increase in oxygen consumption, regional cerebral blood volume and regional cerebral blood flow, increasing the concentration of deoxyhaemoglobin and decreasing the concentration of oxyhaemoglobin (for review see Logothetis & Wandell, 2003; Norris, 2003). By comparing the BOLD response across two or more test conditions (e.g. before and after learning a task), activation in a given brain area can be considered as increased or decreased relative to the control condition. Magnetic resonance imaging (MRI) is also used to acquire an anatomical scan of the brain prior to imaging with fMRI so that the location of any changes in the BOLD signal can be readily identified on a subject-specific basis.

The advantage of using fMRI lies in its unsurpassed spatial resolution (as much as 1 mm accuracy) and its ability to index the connectivity between functionally activated brain regions. This means that one is able to study how different brain areas interact with each other during certain tasks, or how brain activity in different areas changes following an insult to the brain. Studies have demonstrated that while neurological and behavioural tests may not be able to detect changes in brain function following traumatic brain injuries such as concussion, there is increasing evidence that advanced neuroimaging methods can provide more sensitive indications of the underlying brain pathology (e.g. Johnson et al., 2012). These findings suggest that fMRI may show promise as a prognostic tool to evaluate the neurological status of asymptomatic individuals who are suspected of injury (e.g. military personnel who are suspected of developing post-traumatic stress disorder). However, a significant limiting factor of fMRI is the relatively sluggish haemodynamics of blood flow, thus markedly limiting the temporal resolution of this approach. For example, while EEG and MEG allow one to characterise neural response at the millisecond time scale, fMRI operates on a multi-second time scale. Along the same vein, fMRI is only an indirect inference of neural activity (through changes in blood flow) while the other approaches measure neural activity more directly. Recently, new techniques have allowed for the measurement of brain activity via fMRI during interactions with virtual environments (VEs), thereby enabling one to examine whether or not exposure to VEs can influence a damaged brain's activity patterns and levels (e.g. Slobounov et al., 2010; Saleh et al., 2013).

2.2.2.2 Magnetic Resonance Spectroscopy (MRS)

Magnetic resonance spectroscopy (MRS) is a non-invasive imaging technique that uses the nuclear magnetic resonance properties of hydrogen to quantify brain metabolites in vivo. It can be used to study metabolic changes in neuropathies such as brain tumours, strokes and seizure disorders (Cirstea et al., 2011; Federico et al., 1998; Marino, Ciurleo, Bramanti, Federico, & De Stefano, 2011). The neurometabolites detectable by MRS often fluctuate in response to neuronal injury, hypoxia, cellular energy metabolism and membrane turnover (Brooks et al., 2001). These include: N-acetyl aspartate (a marker for neuronal integrity), lactate (a by-product of anaerobic metabolism during periods of hypoxia), creatine (related to the energy potential available in brain tissue), choline (an indicator of cell density and cell wall turnover), myo-inositol (an astrocytic marker and possibly a indicator of intracellular osmotic integrity) and glutamate (the main excitatory neurotransmitter in the central nervous system).

2.2.3 Measuring Changes in Behaviour

The neuroplastic nature of the brain enables the process of learning and re-learning to occur. Because the process of learning is supported by neuroplasticity, change in an individual's behaviour over time is an important index of cortical reorganisation. Indeed, all procedural and episodic learning, and relearning after injury to the brain, is supported by neuroplastic change. Motor learning is an ideal example to illustrate this concept. Motor learning is defined as the acquisition of a new behaviour through skilled practice and results in a relatively permanent change in the ability of an individual to perform a movement (Salmoni et al., 1984; Schmidt and Lee, 2011). Once a skilled movement is learned, the ability to perform the skill is robust and stable. Experience, practice or change in behaviour stimulates the brain to reorganise. Neuroplasticity, in the context of motor learning, refers to changes in neural organisation associated with skilled practice or modifications of movement patterns (Berlucchi and Buchtel, 2009). When a skill is repeatedly practised, neural changes occur as a result of functional reorganisation across many brain regions (Karni et al., 1998). As we will discuss later on (and in Chap. 3), technology such as virtual reality, which has the ability to enforce stereotyped, repeated practice of skills is an excellent method by which to promote learning and rehabilitation (e.g. by using sophisticated forms of feedback, practice schedules, engaging and rewarding practice environments, and the possibility of mass practice) to reinforce and perhaps even bolster neuroplasticity.

2.3 Experience-Dependent Neuroplasticity

2.3.1 Motor Learning and New Technology

Overall, learning and practising new motor skills is critical for inducing neuroplastic change and functional recovery after an insult to the nervous system. There is ample evidence to suggest that plasticity of the brain is dependent on use and that intensity, frequency and duration of practice are all important factors in determining the extent of neural reorganisation (for review see Adamovich, Fluet, Tunik, & Merians, 2009). Given the central role of practice for experience-dependent plasticity there is now acute interest in the development of new techniques, such as virtual reality interfaces, that enable the user to control or modify the task parameters to foster motor learning. These technologies may allow training to occur in a life-like enriching yet controlled environment, integrated into the clinical setting, and tailored to the specific needs of each individual.

2.3.2 Neuroplasticity in the Context of Motor Learning

Importantly, experience appears to be one of the main drivers of neuroplastic change. In fact, substantial short-term changes in the rate of both changes in skill and functional organisation can be observed even within a single training session. In the context of motor learning, "fast learning" (Doyon and Benali, 2005) is the rapid change often seen early in practice; however, this does not necessarily translate to sustained improvements in motor skill. With practice over multiple training sessions, improvement commonly plateaus and the slope of change associated with learning lessens (Karni et al., 1998). This characterises the "slow learning" phase (Doyon and Benali, 2005), which can continue for long periods of time. In addition, following the conclusion of a practice session, motor memories may be strengthened or enhanced by an offline process known as consolidation, which allows memories to stabilise and be available to be recalled at a later date (Brashers-Krug et al., 1996). A key question centres on why the speed of change associated with motor skill acquisition varies within and across practice sessions. Neurophysiology provides the answer. Rapid changes in the amount and location of neurotransmitters, within and between the neurons of the brain support fast learning (Nudo, 2006); while the structural modifications enabling new contacts between neurons underpin slow learning (Kleim et al., 2004). Because altering neuron structure requires more time than does reallocating neurotransmitters, rates of change in behaviour associated with learning vary between early and late learning (Karni et al., 1998).

Overall, an understanding of the mechanisms of neuroplasticity in the context of motor learning is important in designing and implementing tools to promote neuroplastic change. Notably, these properties can be particularly well exploited by technology such as VR to provide user experiences that promote the processes of both fast and slow learning.

2.4 What Is the Role of Virtual Reality in Neuroplasticity?

Generally, following damage to the brain an individual's ability to interact with the physical environment is diminished (Rose, Brooks, & Rizzo, 2005). New technology, such as VR, may potentially help reduce the burden of such physical limitations by providing an alternative, favourable environment in which to practice motor skills. VR can be defined as "an approach to user-computer interface that involves real-time simulation of an environment, scenario or activity that allows for user interaction via multiple sensory channels" (Adamovich, Fluet, et al., 2009).

New VR training approaches capitalise on recent technological advances including improved robotic design, the development of haptic interfaces and the advent of human–machine interactions in virtual reality (Merians, Poizner, Boian, Burdea, & Adamovich, 2006). There are many VR applications currently in use. For example, VR has been used in clinical settings as a training tool for surgeons and as a tool to deliver cognitive, post-traumatic stress disorder and pain therapy (Adamovich, Fluet, et al., 2009; Bohil, Alicea, & Biocca, 2011). It also has the potential to aid in studying processes such as the dynamics of neurodevelopment and neuro-connectivity (Bohil et al., 2011) and to study the neural circuitry underlying certain animal behaviours (Dombeck & Reiser, 2012). VR allows for the possibility of delivering patient-specific opportunities for interaction with the environment via technology such as head-mounted displays or screens which require less set-up and effort than would be needed to provide a patient with an opportunity to interact with the real environment (Rose et al., 2005). It is this naturalistic environment allowing for interactive behaviour while being monitored and recorded that is the primary advantage of implementing VR technology (Bohil et al., 2011). This means VR technology can be used to deliver meaningful and relevant stimulation to an individual's nervous system and thereby capitalise on the plasticity of the brain to promote motor learning and rehabilitation (see Chap. 3).

2.4.1 VR Practice

As discussed above, learning and performing new skills is critical for inducing neuroplastic change and functional recovery after an insult to the nervous system. Virtual reality simulations are particularly effective tools that allow for monitoring of behaviour in three-dimensional space. VR set-ups allow for thorough analysis of the user's actions and the ability to provide guidelines and precise real-time feedback to promote the desired behavioural result. Research has shown, for example, that virtual-reality augmented robotically-facilitated repetitive movement training may potentially aid in improving motor control in patients with moderate to severe upper extremity impairment (who have difficulty performing unassisted movements) (Merians et al., 2006).

The majority of empirical data using VR paradigms has involved persons with chronic stroke or children with cerebral palsy (Chaps. 7 and 10). Virtual reality gaming and task simulations are becoming increasingly popular as a means of providing repetitive intensive practice to chronic stroke patients. This is posited to be a particularly effective form of rehabilitation due to its potential to promote increased interest of participants by virtue of task novelty. This may in turn lead to greater programme compliance, which may ultimately facilitate better clinical outcomes compared to traditional rehabilitation programmes (Adamovich, Fluet, et al., 2009; Merians et al., 2006; You et al., 2005).

2.4.2 Categorisation of VR Technology

Virtual environments (VEs) can be used to present complex, interactive multimodal sensory information to the user (Bohil et al., 2011). In fact, a major development in the use and clinical outcome efficacy of VR came with the addition of tactile