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Université de Montréal

How real is movement in virtual environments?

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Résumé

La réalité virtuelle (VR) en réadaptation est une intervention innovatrice qui permet d'incorporer les éléments nécessaires au rétablissement moteur chez les personnes ayant eu un accident vasculaire cérébral (AVC). Cependant, il n'est pas très bien connu si les mouvements exécutés dans les environnements virtuels (VE) complètement immersifs sont similaires à ceux exécutés dans les environnements physiques (PE). L'objectif de cette étude était de comparer la cinématique des mouvements de pointage réalisés dans un VE à ceux faits dans un PE. Les pointages dans le VE étaient générés dans un casque à réalité virtuelle (HMD) à 3 dimensions. Quinze sujets adultes avec hémiparésie chronique (4 femmes et 11 hommes, âgés de 59 ± 15,4 ans) à la suite d'un ACV, avec un score entre 3/7 et 6/7 pour la section du bras du Chedoke-McMaster (indiquant un déficit moteur de modéré à sévère), ont participé à l'étude. Les participants ont été recrutés dans 3 établissements associés au Centre de recherche interdisciplinaire en réadaptation du Montréal Métropolitain (CRIR). Des sujets sains (6 femmes et 6 hommes, âgés de 53,3 ± 17,1 ans) ont aussi participé à l'étude. La cinématique du bras et du tronc a été enregistrée dans le VE et le PE avec le système d'analyse de mouvement Optotrak (6 marqueurs, 100 Hz, 5 s). La tâche expérimentale consistait à réaliser des mouvements de pointage le plus rapidement et le plus précisément possible vers 6 cibles (12 essais pour chaque cible, dans une séquence aléatoire) placées dans différentes positions devant le participant. Cela a exigé différents patrons de mouvement du bras et présentait différents niveaux de difficulté. Les deux environnements ont été construits de la façon la plus similaire possible. Les mouvements ont été analysés au niveau du patron de mouvement du bras et du tronc (amplitudes de mouvement du coude et de l'épaule, coordination interarticulaire entre le coude et l'épaule, déplacement et rotation du tronc) et de la performance du mouvement du bras (précision, trajectoire, vitesse maximale de l'extrémité). L'analyse statistique a été faite en utilisant une ANOVA 2 x 2 x 6 multivariée avec les facteurs environnement (physique, virtuel) et groupe (sujets sains, sujets hémiparétique) comme variables indépendantes et avec le facteur position de la cible (ipsilatérales, centrales et controlatérales dans les rangées supérieures et inférieures) comme variable dépendante. Les résultats ont montré que, chez le groupe des sujets sains, les mouvements de pointage dans le VE complètement immersif ont été similaires à ceux dans le PE pour toutes les variables mesurées au niveau du patron de mouvement. Des différences significatives ont été observées au niveau de la précision de l'atteinte et dans la trajectoire de l'extrémité quand les mouvements de pointage ont été exécutés vers les cibles controlatérales et au niveau de la vitesse maximale pour toutes les cibles. Chez les sujets ayant subi un ACV, les amplitudes de mouvement du coude et de l'épaule et la vitesse maximale ont été similaires dans les deux environnements. Dans ce groupe, des différences ont été observées au niveau du déplacement et de la rotation du tronc, ainsi que pour la trajectoire et la précision du pointage, et ceci seulement dans les cas de mouvements vers les cibles controlatérales. De plus, la coordination interarticulaire entre le coude et l'épaule a été différente entre les deux environnements lors de la performance des mouvements de pointage vers la cible ipsilatérale inférieure. Aucune interaction entre les facteurs de groupe et d'environnement n'a été observée. Ces résultats indiquent que les mouvements dans les VEs en 3D sont assez similaires aux mouvements en PEs, donc nous pouvons considérer que ces environnements sont valides en ce qui concerne les interventions cliniques en réadaptation et au niveau des études sur le contrôle moteur.

Mots-clés : Réalité virtuelle, cinématique, hémiparésie, membre supérieur

Abstract

Virtual reality (VR) for rehabilitation is an innovative intervention that incorporates the necessary elements to induce motor recovery in patients following stroke. However, it is not very well known whether movements performed in fully immersive VR environments (VE) are similar to those performed in physical environments (PE). The objective of the current study was to compare the kinematics of pointing movements performed in a 3D VE displayed through head-mounted display (HMD) to those of movements performed in PE. Fifteen adults with chronic hemiparesis (4 female and 11 male aged 59 ± 15.4 years old) due to stroke and Chedoke-McMaster Arm Scores ranging from 3-6 out of 7, indicating moderate to severe motor impairment, were recruited from 3 establishments associated with the Centre for Interdisciplinary Research in Rehabilitation of Montreal (CRIR). Healthy subjects (6 female and 6 males aged 53.3 ± 17.1 years old) were also recruited. Arm and trunk kinematics were recorded in both VE and PE with an Optotrak Motion Analysis System (6 markers, 100 Hz, 5 s). The experimental task was to point as quickly and as accurately as possible to 6 targets (12 trials per target, in randomized sequence) placed in different areas in front of the participant, requiring different arm movement patterns and levels of difficulty. Both environment conditions were arranged to be as similar as possible to each other. Movements were analyzed in terms of arm and trunk movement patterns (elbow and shoulder ranges of motion, elbow/shoulder coordination, as well as trunk displacement and rotation) and performance outcome measures (endpoint precision, trajectory and peak velocity). Statistical analyses were done using a multivariate 2 x 2 x 6 ANOVA with environment (physical, virtual) and group (healthy, stroke) conditions as independent variables and with target placement (ipsi, middle and contralateral targets in the upper and lower rows) as the dependent variable. Results indicated that, in the healthy subject group, pointing in the fully immersive VE and in the PE were similar for all movement pattern outcomes. Differences were observed in terms of precision and trajectory straightness when pointing to contralateral targets and in the peak velocity for all targets. In the stroke patient group, elbow and shoulder ranges of motion and movement peak velocity were the same in both environments. For this group, differences in trunk displacement and rotation, trajectory and precision were found only for movements to contralateral targets and in elbow/shoulder coordination only when pointing to the lower ipsilateral target. There were no group by environment interactions. The present findings show that movements in 3D virtual environments are sufficiently similar to movements in a physical environment to consider them as valid environments for clinical rehabilitation intervention and motor control studies.

Keywords : Virtual reality, kinematics, hemiparesis, upper extremity

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List of Abbreviations

2D	Two dimensional
3D	Three dimensional
ADL	Activities of Daily Living
ANOVA	Analysis of Variance
AVM	Arteriovenous malformations
CAREN	Computer Assisted Rehabilitation Environment
CIMT	Constraint Induced Movement Therapy
CLRC	Constance-Lethbridge Rehabilitation Centre
CNS	Central Nervous System
CRIR	Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal
CVA	Cerebrovascular accident
EBRSR	Evidence-based review of stroke rehabilitation
EMG	Electromyography
FOR	Field of regard
FOV	Field of view
HDS	Hamilton Depression Scale
HMD	Head-mounted displays
IRED	Infrared-emitting diode
IRM	Institut de réadaptation de Montréal
JHFE	Johns Hopkins Functioning Examination
JRH	Jewish Rehabilitation Hospital

KP	Knowledge of Performance
KR	Knowledge of Results
LC	Lower contralateral target
LE	Lower Extremity
LI	Lower ipsilateral target
LM	Lower middle target
M1	Motor cortex
PE	Physical Environment
PEDro	Physiotherapy Evidence Database Scale
RCT	Randomized controlled trial
RMS	Root-mean-squared
ROM	Range of motion
SD	Standard Deviation
SPSS	Statistical Package for the Social Sciences
SR	Stretch reflex
SSS	Scandinavian Stroke Study
TEMPA	Test d'Evaluation des Membres Superieurs de Personnes Agées
TS	Task-specific
UC	Upper contralateral target
UE	Upper Extremity
UI	Upper ipsilateral target
UM	Upper middle target

VE	Virtual Environment
VR	Virtual Reality
WCPT	World Confederation for Physical Therapy Congress
WHO	World Health Organization

I would like to dedicate this master thesis to
my parents Edmundo and Ester, my sister
Michele and my brother Luiz Guilherme. I
am the happiest person in the world because
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Chapter 1. Literature Review

1.1. Introduction

Cerebrovascular accident (CVA or stroke) is an ensemble of symptoms caused by the interruption of blood supply to, at least, part of the brain. The interruption of the blood supply has, usually, two origins: ischemic or hemorrhagic. Ischemic strokes are characterized by an obstruction of the blood flow in the brain due to a thrombus (thrombotic stroke) or an embolus (embolic stroke) and represents, approximately 80% of the cases. Less frequent, in about 20% of cases, hemorrhagic strokes occur when a blood vessel on the brain ruptures. Aneurysms and arteriovenous malformations (AVM) are common reasons for those ruptures (Heart and Stroke Foundation of Canada, 2006).

Fifteen million cases of stroke are estimated to occur annually in the world. Of those, 5.5 million people die. Stroke is the third most important worldwide cause of death (10%), after coronary heart disease (13%) and cancer (12%) (World Health Organization – WHO, 2002). In Canada, specifically, it is estimated around 40,000-50,000 new cases of stroke each year (Heart and Stroke Foundation of Canada, 2002).

Besides the high incidence of death, stroke results in another significant consequence Worldwide, five million people post-stroke become permanently disabled every year (WHO, 2002). In North America, stroke represents the principal cause of physical disability in adults (American Heart Association, 2006) and hemiparesis is the most common impairment found on those patients (Krakauer 2005).

The sudden loss of brain function after stroke results in different types and levels of neurological impairments. Jorgensen et al. (1995) observed that, in the first week after stroke, the level of patients' neurological impairments was: very severe for 9%, severe for 12%, moderate for 29% and mild for 50%. These numbers were obtained using the Scandinavian Neurological Stroke Scale (SSS – Scandinavian Stroke Study Group, 1985; (Lindestrom et al. 1991), which takes into account several factors varying from level of consciousness to gait. Deficits after the stroke result in difficulties for patients to perform varied activities. Only 21% of patients are able to perform activities of daily living (ADL) independently and the dependency persists in 48% of patients for at least one year post-stroke (Carod-Artal et al. 2000). Stroke has a significant impact on the patient's and their family's daily life, as well as on society. According to the American Heart Association, the 4.8 million post-stroke patients living in the United States indirectly cost, in 2004, US $20.6 billion, due to the loss of their productivity (American Heart Association, 2004).

Considering upper (UE) and lower extremities (LE) separately, stroke survivors are more dependent for tasks involving the UE. Olsen (1990) noted that, three months after stroke, 32% of patients regained independence of their hemiparetic leg while only 21% regained independence of the hemiparetic arm. These consequences place stroke survivors as the biggest users of rehabilitation services (American Heart Association, 2006) and make disability of the UE an important obstacle to the re-establishment of personal autonomy.

1.2. Post-stroke motor impairments

Motor impairments in stroke patients include: spasticity, abnormal patterns of synergy, incoordination, weakness and loss of sensation. The degree of importance of each factor on movement deficits is not precisely known; however it seems to be variable for every patient.

Spasticity refers to a disorder on the motor system where certain muscles are continuously contracted, producing stiffness or tightness. It is characterized by the combination of hyper-tonicity (increased muscle tone), clonus (a series of rapid muscle contractions) and exaggerated deep tendon reflexes (Levin and Hui-Chan 1992). By definition, spasticity is increased muscle tone caused by the velocity-dependent hyper-excitability of the stretch reflex (SR; Lance 1980). This impairment has been cited as one of the factors that contribute to the voluntary movement deficit in the more affected arm following the stroke (Levin et al. 2000; Musampa et al. 2007). Some studies in single-

(Jobin and Levin 2000; Levin et al. 2000) and double-joint systems (Mihaltchev et al. 2005; Musampa et al. 2007) have suggested that spasticity is one of the consequences of a deficit on the regulation of the SR threshold (Levin and Feldman 1994; Feldman and Levin 1995). Deficits in the regulation of SR thresholds results in an inability to relax muscles in different articular ranges (Levin et al. 2000). Moreover, clinical measures of spasticity (Composed Spasticity Index) were significantly correlated with SR threshold measures (Levin et al. 2000).

Muscle incoordination is frequently present in stroke survivors (Bourbonnais et al. 1992). For some authors, the presence of abnormal muscle coordination patterns is considered to be the primary source of motor dysfunction or global disability in stroke survivors (Dewald et al. 2001). By definition, muscle incoordination is the difficulty to activate the adequate muscles, in a selective way (i.e. spatial recruitment), in the opportune moment (i.e. temporal recruitment) and at an optimal intensity according to the motor task to accomplish. As a consequence, stereotypical movements may occur when stroke survivors attempt to produce an effort with the paretic limb (Brunnstrom 1970). For example, in the upper limb, the flexor synergy consists of forearm supination and elbow flexion associated with shoulder flexion, abduction and external rotation. The extensor synergy is characterized by pronation and elbow extension combined with shoulder extension, adduction and internal rotation.

The elaboration of coordinated movements is accomplished by the progressive mastering of the redundant degrees of freedom available to achieve a desired trajectory and the development of more controllable and stable segments (i.e. trunk and limb; Bernstein 1967). After stroke, patients often present a different interjoint coordination when compared with healthy subjects (Levin 1996; Cirstea and Levin 2000; Levin et al. 2002). Interjoint coordination between elbow and shoulder movements is disrupted when movements are performed by hemiparetic patients into or out of the typical extensor or flexor synergies (Levin 1996). In addition, incoordination has been correlated with the level of motor impairment (Fugl-Meyer Assessment, UE section; Cirstea et al. (2003a). In terms of intersegmental coordination, healthy and stroke subjects present a similar stereotyped sequential recruitment of the arm and trunk in that the trunk began moving simultaneously with or before the hand and stopped moving after the end of hand movement. However, the contribution of the trunk movement to the endpoint displacement is substantially higher in the hemiparetic patients and occurs earlier in the reach. One of the reasons for these differences is the incoordination between hand and trunk in stroke patients (Levin et al. 2002). Muscle weakness has also been studied as a crucial element of the motor impairment in stroke survivors. In the literature, muscle weakness following a stroke is not only described as a loss of maximal strength (Adams et al. 1990; Bohannon 1995), but also as an increased delay of force production (Bohannon 1992; Canning et al. 1999), earlier onset of fatigue (Ingles et al. 1999), an increased perception of effort (Gandevia 1982) as well as a difficulty to generate the optimal force for a specific task (Beer et al. 1999). Furthermore, weakness has also been correlated with deficits on SR threshold regulation, leading to the inability to activate muscles in different joint ranges (Levin et al. 2000).

Although the relation between the UE muscle weakness and the level of motor performance (e.g., Box and Blocks test) in hemiparetic subjects had been described by Mercier and Bourbonnais (2004), the relationship between performance and force production seems to be greater on the lower extremity (Bohannon 2007). In a single-blind, randomized controlled trial, Bourbonnais et al. (2002) observed that a treatment based on force feedback improves LE deficits (gait velocity over a 12-m distance and the longest distance in 2 min) but not on UE deficits (TEMPA, Box and Blocks test, and finger-to-nose test). One of the possible reasons for this result is the relevance of strength of the LE for functional activity performance as compared with UE (Bohannon 2007). For example, to bring food to the mouth requires little strength (Bohannon et al. 1991) and would be expected to improve rapidly with small increases in strength as long as adequate hand dexterity and upper extremity coordination are present.

We cannot exclude the impact of sensory deficits in motor function. Impairment of cutaneous and proprioceptive sensation contributes to the loss of motor function in about 30 to 60% of subjects following a stroke (Shah 1978; Carey et al. 1993; Winward et al. 1999). Proprioception (i.e perception of position and/or movement) is strongly correlated with motor recovery in the paretic limb. Moreover, it is a reliable prognostic sign of motor recovery in the long term (Wadell et al. 1987; Desrosiers et al. 2003). Cutaneous sensation (e.g. vibration sense) is one of the first somatosensory modalities to be affected and to return to normal following a stroke (Boivie et al. 1989; Pause and Freund 1989; Holmgren et al. 1990). For these reasons, the recovery of sensory function is of utmost importance for the complete restoration of motor function.

As a result of the sensorimotor deficits described above, movements are affected at the motor pattern (e.g. range of motion, trunk compensation) and performance levels (e.g., endpoint precision, velocity and trajectory) during pointing movements (Cirstea & Levin, 2000). However, motor deficits and their consequences can be attenuated or even reversed during spontaneous recovery and by physical rehabilitation.

1.3. Motor recovery post-stroke

Physiological or spontaneous recovery is responsible for early neurological functional improvement after the stroke. This process results from resolution of local edema, resorption of local toxins, improved local circulation, and recovery of partially damaged ischemic neurons. The time of spontaneous recovery varies from 1 to 6 months, depending on the severity of the lesion (Teasell et al. 2006). In this sub-acute phase, recovery is relatively rapid and motor improvements are more evident (Nakayama et al. 1994; Jorgensen et al. 1995).

Many studies have suggested that patients reach their maximal physical and functional recovery levels in the sub-acute phase. After this, a recovery plateau is achieved, revealing that motor impairments and function become stable. Some of the most influential studies supporting this idea are those of *The Copenhagen Stroke Study* started on the

1990's. Nakayama et al.(1994) found that patients with mild to severe paresis were not able to improve their UE motor disability (measured with the Barthel Index subscores for feeding and grooming) after the 6th and the 11th weeks, respectively, following the stroke. Jorgensen et al. (1995) noted that recovery of activities of daily living (ADL) did not improve significantly after the 13th month post-stroke.

More recently, however, recovery during the chronic phase (more than 6 months) after stroke has been demonstrated in several studies (Nudo 2003; Michaelsen et al. 2006; Teasell et al. 2006). Later recovery may be possible because of the inherent capacity of the brain to develop new synapses, reorganizing the cortex, in response to learning and experience. This phenomenon is called neuroplasticity (i.e. plasticity) and allows the undamaged region of the cortex to assume the lost function of the damaged cortex. For Nudo (2003), post-stroke neuroplasticity is based on three main concepts. First, the acquisition of skilled movements in a normal animal will induce predictable functional changes within the motor cortex. Second, injury to the motor cortex, as might occur in stroke, induces functional changes in the cortical tissue spared by the injury. Third, these two events interact so that after a cortical injury, the reacquisition of motor skills influences the type and quality of functional plasticity that occurs in the intact, undamaged cortex.

Post-stroke neuroplasticity is possible when cortical areas adjacent and/or remote to the infarct are preserved. However, this is not the only condition in which this phenomenon takes place. A sequence of studies by Nudo and colleagues indicated that enlargement of the adjacent cortical representation occurs when the hemiparetic limb is stimulated through repetitive meaningful movements while disuse of this limb decreases the size of the cortical representation. In the first study, by Nudo et al. (1996a), animals (i.e. squirrel monkeys) were not stimulated to use their more-affected limb and their cortical map was examined before and 3 months after an ischemic infarct in the primary motor cortex (M1). The authors noted that, in those animals, the lack of use of the more-affected hand contributed to the reduction of the digit representation in the intact adjacent cortex. This result supports the result of Liepert et al. (1995), where patients had a diminished representation of the motor cortical area of the anterior tibial muscle after immobilization of the ankle joint. In a second study, Nudo et al. (1996b) restrained the use of the more-affected arm and provided animals with a daily 1-hour rehabilitative program. In contrast to the previous study, the intervention resulted in an enlargement of the hand cortical representation. In a similar study, monkeys with ischemic infarcts on the hand area of M1 had their more-affected arm immobilized with a restrictive jacket; however the animals did not receive any rehabilitative training (Friel et al. 2000). The changes observed in Friel's study were similar to those noted in Nudo et al. (1996a), in which monkeys did not have their more-affected arm restrained; however the changes in the cortical representations were significantly different from those observed by Nudo et al (1996b). The M1 mapping showed a decreased hand representation 1 month after the stroke. The authors suggest that, in addition to limb constraint, task repetition that requires skill re-acquisition is necessary to induce reorganization on the intact motor cortex after stroke.

In fact, repetitive task-specific (TS) practice has been suggested as an important element to improve movement outcomes (Butefisch et al. 1995; Cirstea et al. 2003b; Blennerhassett and Dite 2004; Michaelsen et al. 2006; Wolf et al. 2006). In Blennerhassett & Dite's study, patients undergoing stroke rehabilitation were separated into 2 groups. One group of patients received additional TS practice for the UE while the second group received additional training for the LE. After 4 weeks of additional practice, only the UE group had a significant improvement on the scores of the Jebsen Taylor Hand Function Test (Jebsen et al. 1969) and the Motor Assessment Scale (upper arm and hand items; Carr et al. 1985), suggesting a motor function improvement on the paretic UE. In another study, the efficacy of a rehabilitation program based on repetitive TS practice was demonstrated by Wolf et al. (2006). One-hundred-six stroke patients (3 to 9 months post-infarct) that received the Constraint Induced Movement Therapy (CIMT; Taub et al. 1993) were compared to 116 patients treated with usual and customary care. In the CIMT group, patients had their less-affected arm restricted during 90% of their waking hours over a 14 day period. During this period, patients performed functional task repetitively for, at least, 6 hours per day. Following the training, the motor function improvement (measured with the Wolf Motor Function Test and the Motor Activity Log) was significantly greater for the CIMT group than for the control group with the improvements persisting for 12 months in the experimental group.

Although effective in improving UE motor function, repetitive TS practice, when not well managed, may not promote motor recovery (Cirstea et al. 2003b; Michaelsen and Levin 2004; Michaelsen et al. 2006). In Cirstea et al's (2003b) study, chronic stroke patients performed reaching movement repetitively during a single session, consisting of 70 trials. Kinematics were recorded before, during and 10 minutes after the session (retention test). The results showed that after a short-term series of repetitions, patients with mild-to-moderate hemiparesis (Fugl-Meyer score ≥ 50) executed movements faster, more precisely, more smoothly (less segmentation) and with less variability. For patients with moderate-to-severe hemiparesis (Fugl-Meyer score < 50), movement time, segmentation and movement time variability were also decreased. However, for these patients, improvements in motor performance were accompanied by increased trunk recruitment (compensation) even in a situation where such recruitment was not required for the task. Previous studies have argued that compensatory trunk use may be maladaptive in that it may actually limit the potential for arm motor recovery. Thus the authors suggested that practice alone without particular attention to compensatory strategies may not be sufficient to optimize motor recovery on those patients.

1.4. Feedback

Whether or not a movement is effective can be signaled to the performer via two types of feedback: intrinsic and extrinsic feedback. Intrinsic feedback (i.e. inherent feedback) refers to a person's own sensory-perceptual information. Several sensory processes, including vision, proprioception, touch, pressure and audition, can mediate this information. Intrinsic feedback helps to formulate a person's internal representation of the movement goal he or she is trying to achieve. Extrinsic feedback (i.e. augmented feedback) is information additional to intrinsic feedback that comes from an outside source, such as comments from a therapist or changes in the environment (van Dijk et al. 2005; van Vliet and Wulf 2006).

After stroke, intrinsic feedback systems may be compromised in some patients, making stroke survivors more dependent on extrinsic feedback to guide and to improve their motor performance (Sabari 2001; Flinn and Radomski 2002). The importance of extrinsic feedback on motor learning after stroke has been suggested by some authors (Newell 1991; Schmidt and Lee 1999) and augmented feedback combined with rehabilitation techniques has been investigated in several studies (Armagan et al. 2003; Cirstea and Levin 2007).

Armagan et al. (2003) evaluated the efficacy of electromyographic (EMG) biofeedback treatment in the functional recovery of the hemiplegic hand. In addition to an exercise program using Brunnstrom's neurophysiologic approach, participants were treated with EMG biofeedback or with placebo EMG biofeedback. Both treatments were applied five times a week for a period of 20 days. The results showed significant improvements in impairment and functional measures for both groups after the treatment. However, improvements in the wrist active range of motion and surface EMG potentials of wrist muscles were significantly greater in the EMG biofeedback group.

In another study, by Cirstea and Levin (2007), chronic stroke patients were separated in 2 groups. Both groups practiced repetitive pointing movements during 1 hour per day, for 2 weeks. In addition, the first group received terminal extrinsic feedback focusing on movement precision (i.e. knowledge of results – KR) and the second group received concurrent extrinsic feedback focusing on arm pattern of movement (i.e. knowledge of performance – KP). After the training, only the group that received KP improved significantly in shoulder horizontal adduction and flexion range of movement and coordination between shoulder and elbow movement. These results suggested that motor learning in post-stroke patients is influenced not only by the presence of extrinsic information received during the motor training, but also by type and delivery of this information. Finally, the type of feedback should be adjusted for the stage of learning of the subject (Gentile 1987) and should be able to sustain the patient's motivation during the rehabilitation process which is another very important factor in motor recovery (Solmon and Boone 1993).

1.5. Psychological Factors

Motivation is usually associated with the participants' active engagement in a treatment/training intervention (Maclean et al. 2000) and this engagement is essential to achieve positive rehabilitation results (Chen et al. 1999). Although little research has been carried out on motivation in patients with stroke, in some cases, motivation has been even used as a determinant of rehabilitation outcome (Maclean et al. 2000). The impact of depression on the recovery of ADL functions was demonstrated by Chemerinski et al. (2001). In their study, 171 patients following stroke were evaluated with psychiatric (Hamilton Depression Scale – HDS; Hamilton 1960) and motor function test (Johns Hopkins Functioning Examination – JHFE; Robinson & Szetela 1981) in the second week and 3 or 6 months after the stroke onset. A positive correlation between improvements in HDS and in JHFE tests was observed, suggesting that better motor functional recovery depends also on the patient's mood.

This importance of motivation to re-establish motor function has also been studied in stroke survivors. Barker and Brauer (2005) investigated upper limb recovery from the stroke survivors' perspective. The goal of the study was to determine factors other than medical diagnosis and co-morbidities that contribute to recovery. Twenty-one sub-acute and chronic stroke patients and 9 spouses participated to face to face forums and group or individual interviews, where they were encouraged to comment or answer sentences and questions like: *Think about someone who had a 'good recovery' (or a 'bad recovery') and* *explain why.*; *What factors influence recovery?*; *How do you think we can maximise recovery?*; etc. In contrast to what they usually learn from rehabilitation professionals, patients believe that motor performance can improve even many years after stroke. For them, recovery stops only if the patient "gives up". Practicing exercises regularly, intensively, appropriately and continually and using the arm in everyday tasks are seen by the patients as the means to reach maximal physical recovery. However, according to them, the maintenance of motivation to exercise over a long period of time is a problem. They believe that to overcome such obstacles, it is important to be surrounded by relatives; friends and health professionals who are positive and encouraging. In addition, stroke patients emphasize the importance of feedback received from rehabilitation professionals to keep them motivated to continue training. With this information, the authors suggested that to better promote UE recovery, rehabilitation services need to consistently implement their training program and in some cases use innovative interventions and services.

1.6. Virtual reality training environments

An innovative intervention that incorporates the necessary elements to induce motor recovery (i.e. repetition, task-specificity, augmented feedback and motivation) is virtual reality (VR – i.e. virtual environment, VE). By definition, VR is a multisensorial experience in which a person is immersed in a computer-generated environment. The term "VR" was firstly used by Jaron Lamier, a computer scientist, in 1986 (Riva 2003), however, its history started in the 1960s (Sutherland 1965). In stroke rehabilitation, the use of VR was firstly discussed only in the 1990s (Wilson et al. 1997). Since then, the literature about the use of VR has advanced from articles which primarily described its potential benefits, to articles that describe the development of actual working systems, testing of prototypes, and early clinical results with patients trained in such environments (Holden 2005).

The dynamic and extensive adjustability of VR environments and events make it more advantageous for sensorimotor rehabilitation when compared to conventional environments (i.e. physical environment, PE; Weiss et al. 2004; Holden 2005). Using VR, it is possible to create different tasks that are not easily constructed in PE. It is also possible to provide specific extrinsic feedback in a precise and flexible manner using environmental changes and visual cues (Todorov et al. 1997; Holden 2005). In addition, in VR, environments and tasks can be easily and quickly individualized to patient's motor abilities and preferences, as well as to the goal of therapy (Sveistrup 2004). VR is also a reliable tool that can provide quantitative and qualitative information about the patient's rehabilitation progress (Kenyon et al. 2004). It allows physiotherapists and occupational therapists to better identify the appropriate moment to increase the tasks' level of difficulty for the patients. Allied to the task and environment relevance, the challenging situations provided in VR, where patients receive scores about their performance and think they are playing a video game, are very useful to enhance their degree of interaction with the therapy. This degree of interaction is very important for positive rehabilitation outcome since the level of a patient's commitment to therapy is negatively influenced by boredom, fatigue, and lack of enthusiasm (Tinson 1989). Thus VR seems to be a valuable tool in clinical setups where rehabilitation professionals need to create motivating interventions for their patients. Finally, besides being advantageous for the performance of repetitive tasks in motivating environments, VR also allows the patients to perform tasks in safe conditions where they are not exposed to risks presented in some conventional tasks (Sveistrup 2004).

Virtual experience is possible only because of the use of special hardware and software. Input interfaces such as tracking systems (e.g. Optotrak Motion Capture System – Northern Digital; Fastrak – Polhemus Corp; Cyberglove Immersion Corp.) allow movements to be tracked so that users can interact with objects in the VE. Users perceive the VE with output interfaces such as head-mounted displays (HMD), flat screen displays, audio speakers etc (Riva et al. 2004). Although outputs are possible for all the senses, visual and auditory stimuli are the most frequently used in VR systems (Weiss and Katz 2004). Finally, computers and software are necessary to integrate all those equipments.

In the literature, different VR systems have been described, varying according to the level of immersion delivered to the users. In more immersive VR systems, users can better experience a neuropsychological phenomenon known as *presence* (Riva 2003; Holden 2005). *Presence* is defined as the "sense of being there" and is suggested as an essential element for the transfer of learning from VE to PE (Stanney et al. 1998; Riva 2003). Since vision is the most important sense for immersion in the virtual experience, the meaning of visual displays is very significant. Thus, VR systems such as those where visual output is displayed in 2D by desktop, flat screen or projection systems are considered non-immersive or less-immersive. In contrast, an HMD system is a fully-immersive VR system where the user sees only the computer-generated image (Keshner 2004). In addition to permitting the subject to interact with a 3D VE, this system allows users to take advantage of stereoscopic vision so that the distance between objects can be perceived (Riva et al. 2004). Also, the HMD system provides a bigger field of regard (FOR) when compared to less immersive systems. It is achievable because the head position and orientation tracking relies on changes in the VR viewpoint when the user moves her/his head (Riva et al. 2004). CAVE^{TM} systems (Cruz-Neira et al. 1992) and the video capture VR system (Weiss et al. 2004) are other examples of immersive VR systems.

Although there are only a few clinical studies to date using VR therapy, it has been suggested that training in VR may improve UE motor function in patients following stroke (Foley et al. 2007; Henderson et al. 2007). In a systematic review, Henderson investigated the evidence of using immersive and non-immersive VR to increase UE motor performance and function in patients with acute, sub-acute or chronic hemiparesis following stroke. A total of 6 articles met the inclusion criteria (i.e. be published in English-language scientific literature; have an element of retraining of arm movements and not hand movements alone; do not use other types of training interfaces performed in non-virtual environments), including two randomized controlled trials (RCTs; Piron et al. 2003; Jang et al. 2005), one single subject design (Broeren et al. 2004), and three pre-post design studies (Holden et al. 1999; Holden and Dyar 2002; Piron et al. 2005). Results indicated evidence from one good quality RCT (PEDro score ≥6) and one single subject study suggesting a greater benefit from training in immersive VR compared to no therapy. On the other hand, for training in non-immersive VR compared to no therapy, conflicting evidence was observed from three studies using a pre-post design. Although limited, the results are sufficiently encouraging to justify further research efforts in this area.

Evidence of the effectiveness of training in VR was also evaluated by Teasell and colleagues in the *Evidence-based review of stroke rehabilitation* (EBRSR). However, in this review, in addition to the studies analysed in Henderson's study, studies were also included where only hand movements were trained (Jack et al. 2001; Merians et al. 2002; Merians et al. 2006; Fischer et al. 2007). The analyses indicated strong evidence (indicated by at least two good-to-excellent quality RCTs – PEDro score ≥6) that VR treatment can improve UE motor function in the chronic stages of stroke.

Even if the results presented above are encouraging, more studies about behaviour and movement characteristics in VR are necessary to better understand the applicability of this tool in clinical rehabilitation and motor control studies. Viau et al. (2004), compared movement kinematics of identical tasks made in PE and VE. The goal was to validate a non-immersive VR as a tool for studying reaching and grasping in healthy subjects and in individuals with hemiparesis. In both environments, participants grasped a ball (real or virtual) from the edge of a table (real or virtual), reached forward by leaning the trunk and then placed the ball within a target (real or virtual). The representation and orientation of the subject's hand in the 2D environment was obtained using a Cyberglove (Immersion Corp.) and a Fastrak (Polhemus Corp.) electromagnetic sensor. Also, prehension force feedback was provided to the participants by a Cybergrasp (Immersion Corp.). The movements were evaluated in terms of endpoint path curvature, maximal grip aperture, trajectory length, angular ranges of joint motion and elbow-shoulder interjoint coordination. The results presented a certain similarity in movement kinematics between physical and virtual reaching and grasping. However, both healthy and stroke participants used significantly less wrist extension and more elbow extension in VE during the ball transportation and release phases. One of the reasons indicated for those changes on the movement pattern was the absence of depth perception in the VR condition. For the authors, the participants could not estimate the correct distance between them to the wall on the 2D VE, leading to movement compensations. In addition, Viau et al. argued that differences found in this study would not exist in 3D immersive VR where stereoscopic vision is provided, such as those visualized through a HMD.

Chapter 2. Rationale, Objective and Hypothesis

2.1. Rationale for the study

As summarized in the literature review section, stroke is one of the major causes of physical disability in adults worldwide. After stroke, the hemiparetic upper extremity (UE) remains an obstacle to the re-establishment of the patient's autonomy. The lack of independence of stroke survivors has a significant impact on the patient's and their family's daily life, as well as on society. It places those patients as the biggest users of rehabilitation services (American Heart Association, 2006).

Motor impairments like spasticity, abnormal patterns of synergy, incoordination, weakness and loss of sensation affect what motor patterns are used to produce movement (e.g. range of motion, trunk compensation) and motor performance variables (e.g., endpoint precision, velocity and trajectory). These sensorimotor deficits can be attenuated or even reversed after the stroke by experience-dependent plasticity in the CNS that can be induced through motor training tasks even 6 months post lesion (i.e. chronic phase). However, some elements such as task-specificity and relevance, task repetition, feedback and motivation must be incorporated into motor training approaches to make them more effective.

An innovative intervention in which these elements can be easily integrated is virtual reality (VR). VR is a multisensorial experience in which a person is immersed in a computer-generated environment. In VR, environments and tasks are simply and quickly individualized to patient's motor abilities and preferences, as well as to the therapeutic goal. In addition, VR enhances the degree of interaction between the patient and therapy. This degree of interaction is important for increasing the efficacy of rehabilitation and is negatively influenced by boredom, fatigue, lack of enthusiasm and lack of cooperation.

The efficacy of VR as a tool to improve UE motor function of patients in the chronic stages of stroke has been supported in the literature (Foley et al. 2007; Henderson et al. 2007). However, it is not very well known whether movements performed in VR are similar to those performed in physical training environments. This information is necessary to better understand the applicability of this tool in clinical rehabilitation and motor control studies. In a previous study (Viau et al. 2004), the kinematics of reaching and grasping movements performed in a two dimensional virtual environment (VE) presented some differences compared to those of the same movement performed in a physical environment (PE). The probable reason for the differences was the absence of depth perception in the 2D VE which was displayed to the participants on a computer monitor. Considering the limitation of the VR system in the previous study, it is appropriate to investigate UE movement kinematics in a 3D immersive VR where stereoscopic vision is provided, such as that visualized through a head-mounted display.

2.2. Objective

The objective of the current study was to compare the kinematics of pointing movements performed in a 3D fully-immersive (HMD) VR system to those of movements performed in a PE (i.e. conventional condition) in healthy subjects and in subjects with motor deficits due to stroke-related brain damage. The purpose of this study was not to determine the differences in arm kinematics of pointing movements between healthy subjects and stroke survivors since these differences have been previously well-documented.

2.3. Hypothesis

Since a 3D immersive VE provides stereoscopic vision to the users (depth perception), we hypothesized that there would be no differences in the kinematics of pointing movements performed in a 3D immersive VE and a similar PE in healthy subjects or in subjects with motor deficits due to stroke-related brain damage.

Chapter 3. Methods

3.1. Study Sample

The differences between the physical and virtual environments (PE and VE, respectively) were investigated in two different populations: 1) Patients following stroke and 2) healthy subjects. Fifteen stroke patients with hemiparesis (4 female and 11 male aged 59 ± 15.4 years old; Table 1) were recruited from three rehabilitation centers associated with the *Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal* (CRIR). Twelve healthy subjects (6 females and 6 males aged 53.3 ± 17.1 years old) also participated in the study. Ethics approval was obtained from the CRIR (Annex I) and all subjects signed an informed consent form (Annex II) prior to participating. In order to be eligible for the study, the participants had to fit the inclusion and exclusion criteria detailed below.

Table 1. Demographic and clinical description of participants with stroke. 'F' female, 'M' male. 'MC artery' middle cerebral artery

Subject	Genre	Age (years)	Site of lesion	Duration (months)	Hand dominance	Side of hemiparesis	Chedoke McMaster score[a]	Fugl-Meyer score[b]	Composite spasticity index[c]
P1	F	75	Temporal parietal	24	Right	Left	5	59	4
P2	M	49	Basal ganglia	11	Right	Right	6	65	5
P3	F	60	Subcortical	21	Right	Right	5	53	8
P4	F	80	MC artery	14	Right	Right	5	61	7
P5	M	57	Subcortical	14	Right	Right	5	57	6
P6	M	67	Parietal	26	Left	Right	4	54	10
P7	M	77	MC artery	73	Left	Left	4	47	4
P8	M	40	MC artery	30	Right	Left	5	49	8
P9	F	30	MC artery	101	Right	Right	4	41	12
P10	M	45	Basal ganglia	12	Right	Right	4	50	8
P11	M	70	MC artery	40	Right	Left	3	29	7
P12	M	78	Subcortical	32	Right	Left	3	19	8
P13	M	45	Subcortical	13	Right	Left	6	58	4
P14	M	51	MC artery	18	Right	Right	5	57	5
P15	M	61	Parietal	64	Right	Left	6	59	7

[a] Arm section of the Chedoke McMaster score (7 = normal arm activity)

[b] Upper Limb section of the Fugl-Meyer score (66 = normal arm function)

[c] Composite Spasticity Index (4 = normal tone)

3.2. Inclusion and exclusion criteria

Inclusion criteria for the stroke patients were:

1. be between 18 and 81 years old;
2. have had a single stroke more than 6 months previously (i.e. chronic stroke);
3. have a score between 3 and 6/7 in the Arm Section of the Chedoke-McMaster Stroke Assessment Scale, indicating a moderate hemiparesis (Gowland et al. 1993).

Exclusion criteria for stroke patients were:

1. have a lesion in the cerebellum or the occipital lobe;
2. have marked apraxia or aphasia;
3. have an orthopedic or neuromuscular problem in the arm and/or trunk;
4. have attention deficits or uncorrected visual problems;
5. be unable to speak or understand English or French.

Inclusion criterion for healthy subjects was:

1. be between 18 and 81 years old.

Exclusion criteria for healthy subjects were:

1. have pain in the arm and/or trunk;
2. have an orthopaedic, neuromuscular or neurological problem in the arm and/or trunk;
3. have attention deficits or uncorrected visual problems;
4. be unable to speak or understand English or French.

3.3. Recruitment of participants

Stroke patients

The recruitment of stroke subjects started by screening the medical charts from three rehabilitation centres: Jewish Rehabilitation Hospital (JRH), *Institut de réadaptation de Montréal* (IRM), Constance-Lethbridge Rehabilitation Centre (CLRC). After potential participants were identified (according to the inclusion and exclusion criteria), the clinical research coordinator from each rehabilitation centre contacted the patients through an informative letter about the project (Annex III). In the letter, the project was described to the patients and they were invited to contact one of the project team members if they were interested in participating or receiving more detailed information about the study. Following the conversation with the team member, interested individuals were invited to go to an initial screening assessment at the research centre of the JRH. Subjects meeting study criteria signed the consent form and an appointment was set up for the next laboratory visit.

Healthy subjects

Healthy subjects who were interested in participating responded to announcements (Annex IV) that were posted on bulletin boards at the JRH and IRM. The same procedure for obtaining consent was followed.

3.4. Experimental protocol

The experimental protocol consisted of clinical assessment (only in the stroke patients group) followed by the kinematic data collection, which was done in two environments (i.e. PE and VE) and finally, of a questionnaire, filled in by the participants, about how they interacted with and appreciated the virtual experience.

Clinical measurements

Prior to the experiment, all stroke subjects were assessed by research clinicians using a series of clinical tests to determine the level of motor impairment and function of their affected upper limb. In total, these evaluations took around 30 minutes and were done at the JRH.

The motor recovery level of the hemiparetic upper extremity (UE) was evaluated with the Fugl-Meyer Upper Limb Scale (Duncan et al. 1992). This evaluation measures the capacity of the patient to produce movements voluntarily, selectively, in a coordinated fashion and out of pathological synergies. According to this scale, UE motor function is considered normal if the subject reached the maximal score of 66 points (Fugl-Meyer et al. 1975).

Spasticity of the elbow muscles was assessed using the Composite Spasticity Index. This valid (Nadeau et al. 1998) and reliable test measures spasticity by: the resistance felt during stretch of the passive elbow flexors, the excitability of the biceps brachial tendon reflex, as well as wrist flexor muscle clonus. A score of 4/16 indicates normal tonus, while a score of 16/16 means severe spasticity (Levin and Hui-Chan 1993).

Kinematic recording

Movement kinematics were recorded using the Optotrak Motion System Analysis (Northern Digital Corp., Type 3020) at a frequency of 100 Hz. This system is composed of markers (i.e. infrared-emitting diodes; IREDs) and three optical cameras able to capture the information emitted by the markers in three dimensions (x, y and z planes).

To record the participant's arm and trunk movements, 6 IREDs were placed on: tip of index (distal phalange of the index finger, i.e., endpoint), wrist (styloid process at the head of radius), elbow (lateral epicondyle), ipsilateral and contralateral shoulders (acromion processes) and trunk (middle of sternum) (Figure 1).

Data recording started at the same time that the participant received the command to begin the movement and lasted for 5 seconds.

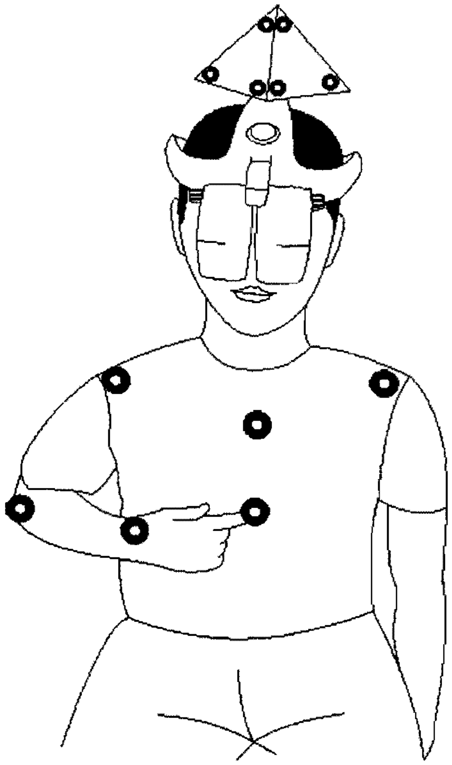


Figure 1. IRED placement and task start position.

Physical environment

Given that the goal of the study was to compare kinematics of pointing movements in two different environments, the PE and VE were created to be as similar as possible to each other.

In the PE, six 6 x 6 cm square targets were attached to an adjustable support (Figure 2) and arranged in 2 rows and 3 columns. The squares represented the targets to which the participants should point. The top squares were labelled with the numbers 1, 2 and 3 and the bottom targets were labelled with the numbers 4, 5 and 6 (Figure 3). The grid of squares was positioned in front of the participant such that the middle squares (i.e. targets 2 and 5) were aligned to the sternum of the participant and the midline between the top and bottom squares was aligned with the participant's shoulders. The most important feature was that the distance between the participant and the midline point was equal to the length of the subject's arm (i.e. from the acromion to the tip of the index) plus 5 cm. An additional 5 cm was added to the arm length in order to avoid physical contact of the fingertip with the target. Finally, the distance between the centers of adjacent squares was 26 centimetres (Figure 3).

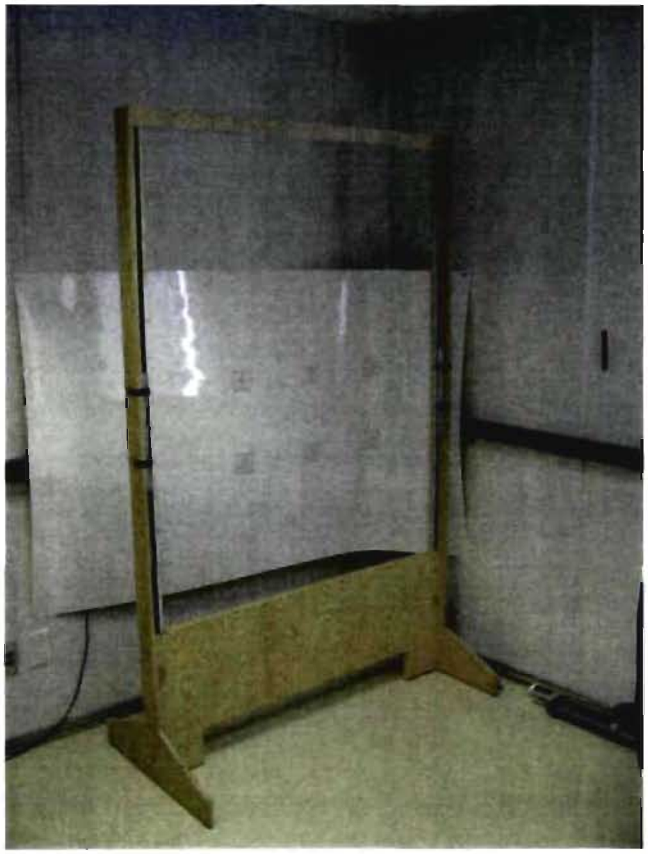


Figure 2. Physical environment setup.

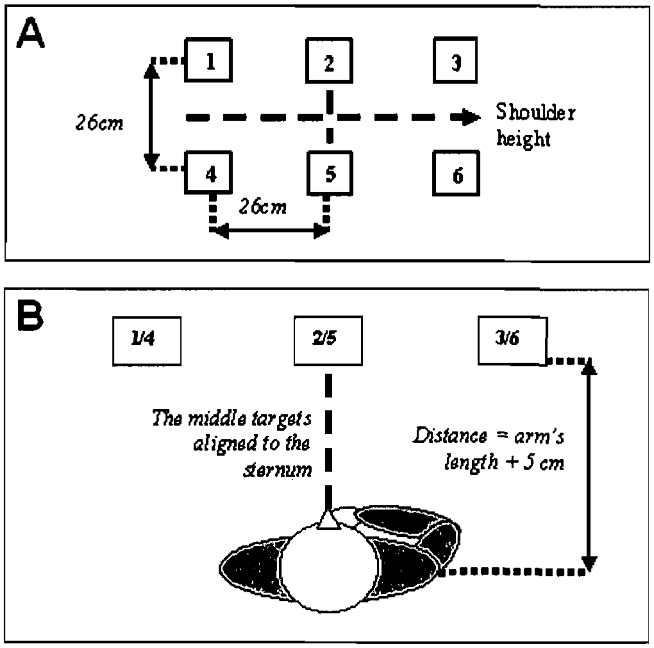


Figure 3. Target arrangement on coronal (A) and transversal (B) planes.

Virtual reality environment

The virtual reality environment (VE) consisted of a 3D environment generated by a PC computer (Dual Xeon 3.06 GHz, 2 GB RAM, 160 GB hard drive; Figure 4) and displayed to the user through a head-mounted display (HMD; Kaiser XL 50, resolution 1024 X 768, frequency 60 Hz; Figure 5). The head position and orientation in the virtual space were reproduced by an optical tracker (i.e. Optotrak). One rigid body, composed of 6 IREDs was attached to the HMD (Figure 5). The endpoint was represented in the VE by a blue dot, obtained from the IRED on the tip of the index finger (Figure 6). This was the only body cue indicated to the users when they were immersed in the VE. The data created by these interfaces were integrated by CAREN software (Computer Assisted Rehabilitation Environment), developed by Motek BV. The system also included a dual-head Nvidia

Quatro FX3000 graphics card (70 Hz) providing high-speed stereoscopic representation of the environment that was created on SoftImage XSI.

The scene in the VE consisted of 6 targets of the same dimensions and displayed in the same array as that described for the PE, except that they appeared as elevator buttons arranged on a virtual elevator wall. The scene was calibrated so that the target locations in the 3D space were exactly the same as in the PE with respect to the distance from the participant's body (Figure 7; Subramanian et al., 2007).

Figure 4. PC computer used to create the VE.

Figure 5. HMD used to display the VE to the user; and the rigid body with the IREDs used to reproduce the position and orientation of the head in the VE.

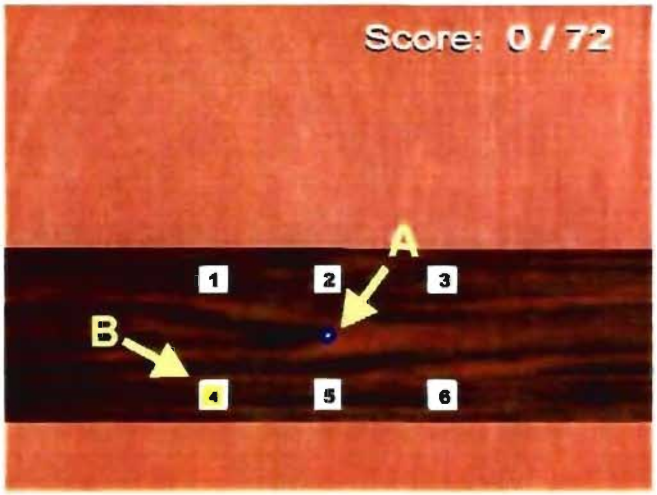


Figure 6. Endpoint visual representation in VE (blue dot: A); and the visual command used in VE to indicate the beginning of the trial (B).

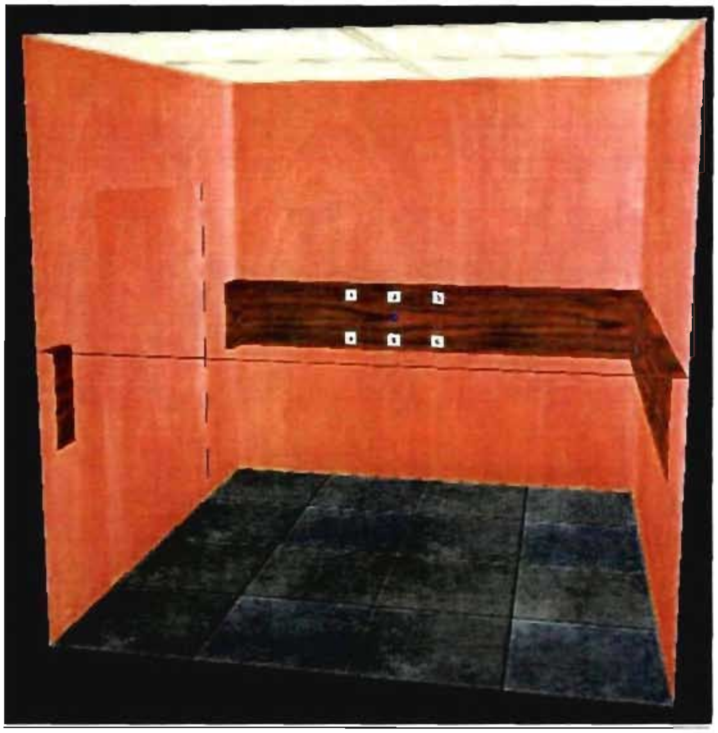


Figure 7. Virtual environment (i.e. virtual elevator).

Experimental procedure

Subject Position

During the experiment, participants were comfortably seated on a chair with approximately 90° of hip and knee flexion and with the feet supported on the ground. Prior to each trial, participants had to place the tip of their index finger on their xiphoid process so that the arm was in approximately 50° of shoulder abduction and 0° of flexion, 120° of elbow flexion and the forearm and the wrist were in neutral position (Figure 1).

The task

Participants in each group were asked to perform the same task in both environments (i.e. PE and VE). The task consisted of 72 trials (3 blocks of 24 trials) of pointing movements toward the 6 different targets (12 trials per target). The target sequence and the order of presentation of environments were randomized to avoid learning effects. The task was designed so that forward trunk displacement was not necessary, since the goal was to point to and not to touch the targets. This pointing movement task was chosen because it required the coordination of multiple arm joints, an ability that should be re-acquired during recovery from stroke (Cirstea et al. 2003a).

Prior to the beginning of the experiment, the participants were instructed to execute the movements as accurately and as fast as possible. While stroke patients performed the task with their more affected UE, healthy subjects used their non-dominant UE. We chose to investigate the non-dominant UE of the healthy subjects since this limb is less skilful than the dominant UE and so, more comparable to patient's condition.

The target arrangement caused the participants to produce movements of different levels of difficulty using different patterns of movement. For example, the upper row of targets (i.e. 1, 2 and 3) required more shoulder flexion than the lower row. In addition, the targets placed on the ipsilateral side of the evaluated arm required shoulder horizontal abduction combined with elbow extension and those on the contralateral side required shoulder horizontal adduction combined with elbow extension (Figure 8).

The target to be pointed at was indicated at the beginning of each trial by an auditory go signal emitted by the computer (e.g., 'six' meaning 'point to target 6'). Information about successful pointing attempts in terms of precision (i.e., finger arrived within the 6"x6" target) and speed (within 5 s) were indicated to the subject by a 'ping' sound generated by the computer. In addition, in the VE, a concurrent visual command was also used to indicate the target to the participant (Figure 6). Following the start command, the participant had 5 seconds to complete the pointing trial. As soon as the trial was completed or after 5 seconds, the participants had to resume the starting position and be ready for the next trial.

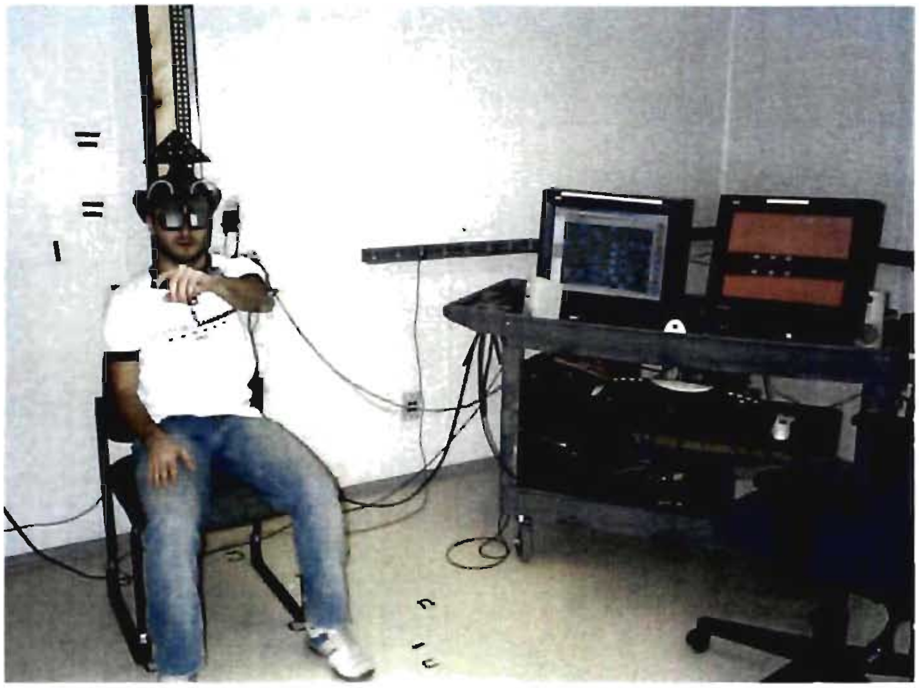


Figure 8. Subject performing the pointing movement toward a contralateral target in the VE.

Data collection

During the experiment, the pointing task was performed in both environments. Thus, every participant had to execute 72 trials in the PE and 72 trials in the VE, for a total of 144 trials. In order to avoid learning and fatigue effects, the order of the experimental environment was randomized. In addition, to avoid fatigue during or after the data collection, the task was separated into 3 blocks of 24 trials, with a 3 min pause between blocks. If needed, additional pauses were given to the participants.

Prior to beginning the experiment in the VE, each participant practiced some trials in this condition to become familiar with the HMD and the VE. Motion sickness symptoms, termed cybersickness (i.e. nausea, vomiting, headache, somnolence, loss of balance, etc.), have been reported when subjects view a VE through an HMD (ref). These symptoms were prevented during the experiment because of the following factors. Since longer latencies for acquiring positional data may be associated with cybersickness, the first preventive factor was the use of the Optotrak tracking system. Optotrak provides higher sampling rates and shorter latencies compared to other systems, e.g., electromagnetic (Subramanian et al. 2007). Also, the possibility of cybersickness was reduced because the VE had almost no oscillations (Lo and So 2001) and the helmet was worn for less than 20 minutes (Regan and Price 1994) during the experiment. Finally, research team members were always in contact with the participants to detect possible symptoms of cybersickness.

Presence Questionnaire

After the kinematic data collection, participants completed a questionnaire about how they interacted with and appreciated the virtual experience. This questionnaire (Annex V) consisted of 10 statements and is an adapted version of the *Presence questionnaire* (Witmer & Singer 1998). For each statement, an eight-point Likert scale was used in which the level of agreement varied from "not at all" (i.e. score 1) to "completely" (i.e. score 8). The statements, which were analysed separately, were:

1) I felt accustomed to the environment when the experiment started.
2) The quality of the images that I saw made me feel as if I was in an elevator.
3) The movement of the virtual hand (blue dot) reproduced the movement of my real hand.

4) I could estimate the distance between me and the buttons on the wall.
5) I was able to recognize the sounds while I was performing the movements.
6) The activity of performing pointing movements towards virtual buttons of an elevator provides a more pleasant training environment for arm movement.
7) I was comfortable when I wore the helmet and the glasses.
8) I felt that the movements produced in the virtual reality training environment were similar to those that I often perform in a physical setting.
9) I enjoyed practicing in the virtual environment and would like to continue the training.
10) I was so engaged in trying to successfully complete the task that I was unaware of any activity or distractions that occurred around me.

3.5. Data analyses

Kinematic parameters used to compare the movements performed in PE and VE were separated in 2 groups: performance outcomes and movement pattern outcomes. Performance outcomes consisted of: endpoint (i.e. tip of index finger) precision, peak velocity and trajectory. Movement pattern outcomes were: elbow and shoulder range of motion (ROM), trunk displacement and rotation, as well as interjoint coordination between elbow extension and shoulder horizontal adduction.

First of all, in our analyses, we considered the beginning and end of the endpoint movement as the times at which the endpoint tangential velocity surpassed and remained above or fell and remained below 10% of the peak velocity. The tangential velocity of the endpoint and trunk were computed from the magnitude of the velocity vector, obtained by numerical differentiation of the x, y and z positional data for markers placed on the index finger and sternum, respectively.

Data analysis was done by one person using *LabView* software *(National Instruments).*

Performance outcomes

Endpoint precision: was calculated in terms of absolute error and was computed as the root-mean-squared (RMS) distance between the final position of the tip of the index and the center of the target.

Endpoint peak velocity: was calculated from tangential velocity traces.

Endpoint trajectory: was determined by the *index of curvature* (ratio of the actual length of the endpoint path to the length of a straight line joining the initial and final positions), which has been shown to better characterize trajectories than area measurements (Archambault et al. 1999). An ideal straight line has an index of 1 whereas that of a semicircle has an index of 1.57.

Movement pattern outcomes

Elbow flexion/extension ROM: was calculated based on the angles formed by 2 vectors between the wrist-elbow IREDs and the ipsilateral shoulder-elbow IREDs. The maximal elbow extension was defined as 180°.

Shoulder flexion/extension ROM: was calculated based on the angles between the vectors formed by the elbow-ipsilateral shoulder IREDs and the vertical axis of the ipsilateral shoulder in the sagittal plane. The position with the arm alongside the body was defined as 0°.

Shoulder horizontal adduction/abduction ROM: was calculated based on the angles between the 2 vectors formed by the elbow-ipsilateral shoulder IREDs and the contralateral shoulder-ipsilateral shoulder IREDs in the horizontal plane. Zero degrees of shoulder horizontal adduction was indicated by the arm in a position following the line joining the IREDs placed on the shoulders.

Trunk displacement: was measured in millimetres and computed from the IRED on the sternum as the distance moved between the beginning and end of trunk movement as defined above.

Trunk axial rotation: was defined as the angle of rotation of the vector joining the two shoulder IREDs with respect to the coronal plane. The initial position was defined as 0°.

Interjoint coordination: was defined as the slope of elbow extension versus shoulder horizontal adduction relationship that was computed using quadratic regression analysis. A slope of one indicates that both joints contributed equally to the movement while a slope different from one indicates that the movement involved predominantly one of the joints. This relationship was chosen because it is the more complicated coordination in pointing movements, since it involves movements in two planes (i.e. horizontal and sagittal; Cirstea et al. 2003b).

3.6. Statistical analyses

Comparison between pointing movements executed in PE and VE was done using a multivariate 2 x 2 x 6 ANOVA with group (healthy, stroke) and environment (PE, VE) as independent variables and target (n=6) as the dependent variable. The data obtained for each target could not be analysed together because, when performing the task, the participants executed movements toward each target with different movement patterns. For example, to point to ipsilateral targets, participants combined elbow extension and shoulder flexion and horizontal abduction; while contralateral targets required elbow extension and shoulder flexion and horizontal adduction. Since the goal of the study was to compare the environments and not the groups, between-group analyses were done only to measure group by environment interactions. In addition, descriptive analyses (i.e. median and mode) were used to explore the data obtained with the questionnaire applied after the virtual experience.

Chapter 4. Results

4.1. Kinematics of pointing movements

Analysis of group by environment interactions revealed no differences for all outcomes investigated: endpoint peak velocity ($F_{6,45} = 0.490$, $p = 0.813$), endpoint precision ($F_{6,45} = 1.238$, $p = 0.305$), trajectory straightness ($F_{6,45} = 0.867$, $p = 0.526$), elbow/shoulder interjoint coordination ($F_{6,45} = 1.885$, $p = 0.104$), elbow extension ($F_{6,45} = 0.555$, $p = 0.764$), shoulder flexion ($F_{6,45} = 0.393$, $p = 0.879$), shoulder horizontal adduction ($F_{6,45} = 0.447$, $p = 0.843$), trunk flexion ($F_{6,45} = 0.414$, $p = 0.866$) and trunk rotation ($F_{6,45} = 0.315$, $p = 0.926$).

Healthy subjects

The results obtained from the healthy subjects group indicated that, in general, pointing movements were performed similarly in PE and VE. First, through the interjoint coordination analysis, it was remarked that, at the beginning of the movement, shoulder horizontal adduction made a greater contribution than elbow extension (Figure 9). This pattern occurred in 100% of the movements in PE and 92% of the movement in VE. No differences were found when pointing movements to the 6 virtual targets were compared to those executed toward the 6 physical targets ($p > 0.05$). Trunk displacement and rotation during the task execution, as well as elbow flexion/extension, shoulder flexion/extension and horizontal adduction/abduction range of motion from the start to the end of the movement were similar in PE and VE ($p > 0.05$) (Figures 10A, 11A, 12A, 13A and 14A, respectively). In addition, no statistical differences between movements made in each environment were found for the coordination between elbow extension and shoulder horizontal adduction ($p > 0.05$) (Figure 15A).

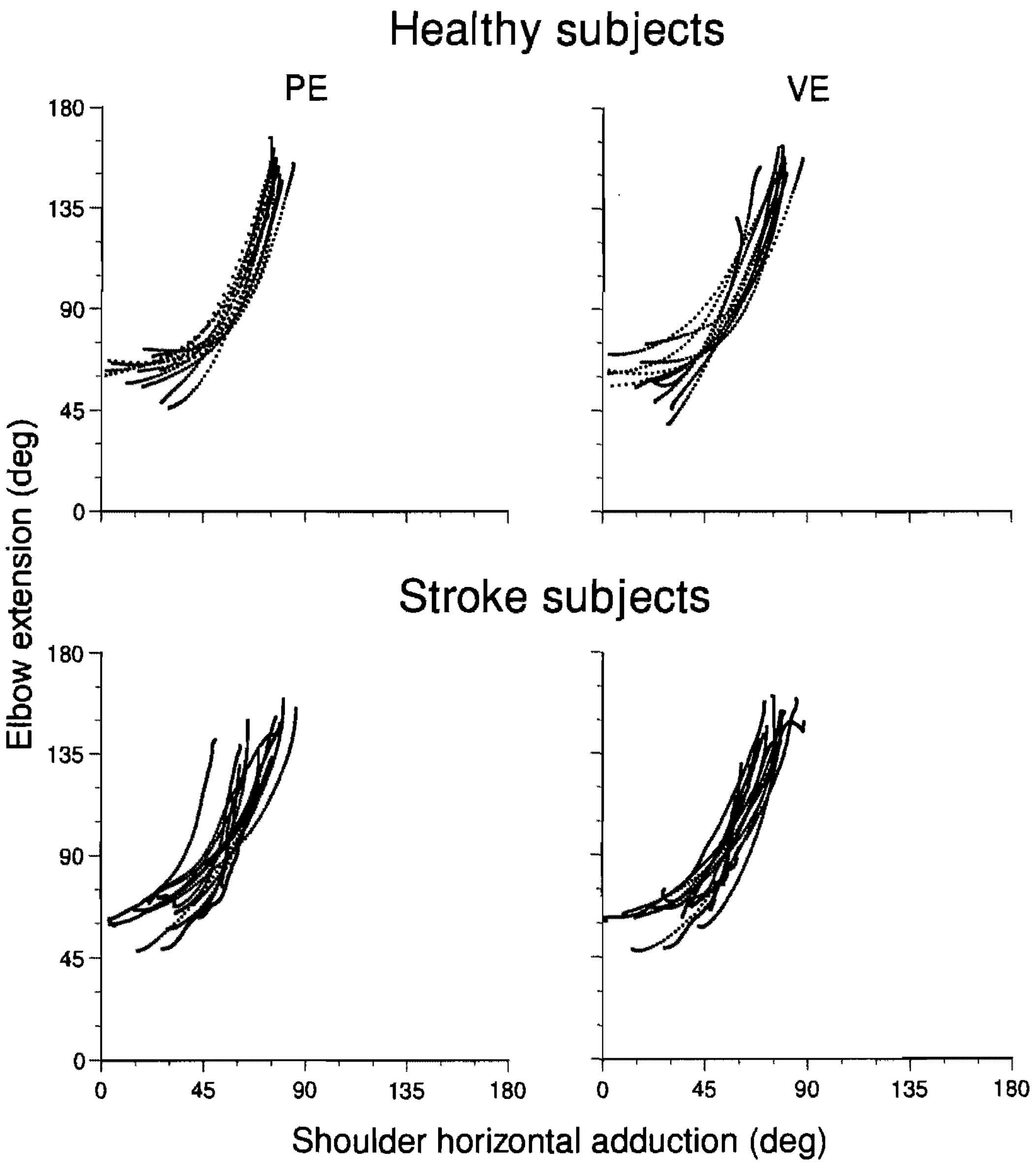
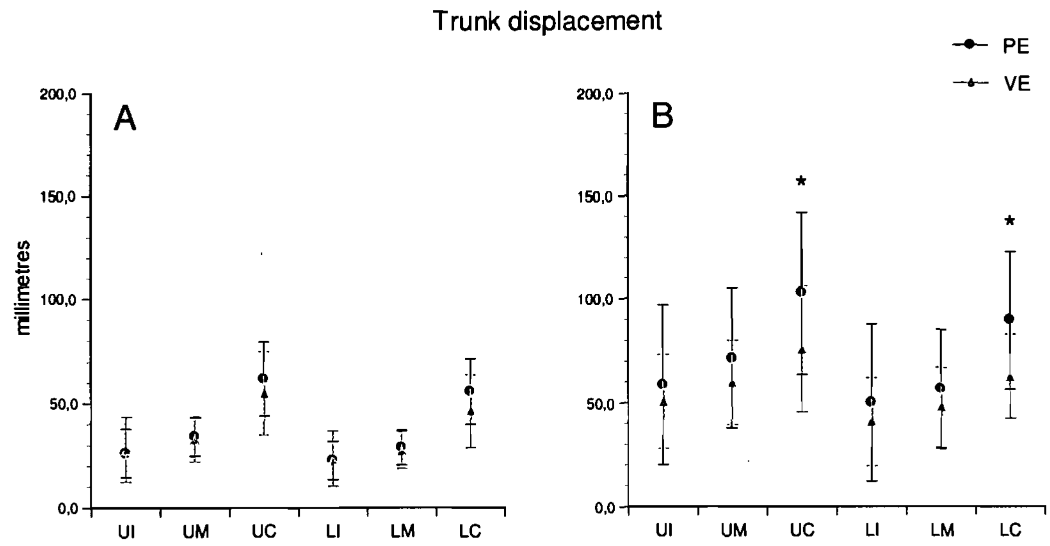


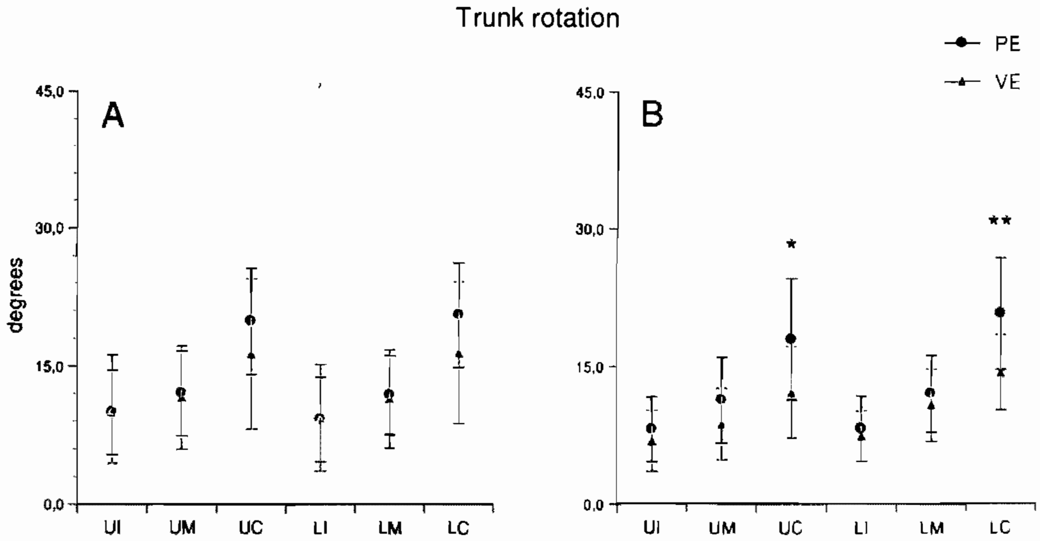
Figure 9. Elbow extension and shoulder horizontal adduction coordination of the pointing movement executed toward the lower middle target in 12 healthy subjects and 15 stroke patients in physical (PE) and virtual (VE) environments.

Concerning the performance outcomes, differences between the movements executed in PE and VE were observed in endpoint trajectory and precision only for contralateral targets. The curvature of the endpoint trajectory was more accentuated in VE than in PE when the movement was performed toward the upper contralateral (UC) target ($p \leq 0.05$) (Figure 16 and 17A). In addition, the pointing movements were less accurate in VE than in PE for the UC ($p \leq 0.05$) and lower ($p \leq 0.01$) contralateral (LC) targets (Figure 18A). Finally, in terms of endpoint peak velocity, differences were found for all targets. Movements were slower in VE than in PE ($p \leq 0.05$) (Figure 19A). A summary of the statistical values from the healthy subjects' data are presented in Table 2.


Trunk displacement

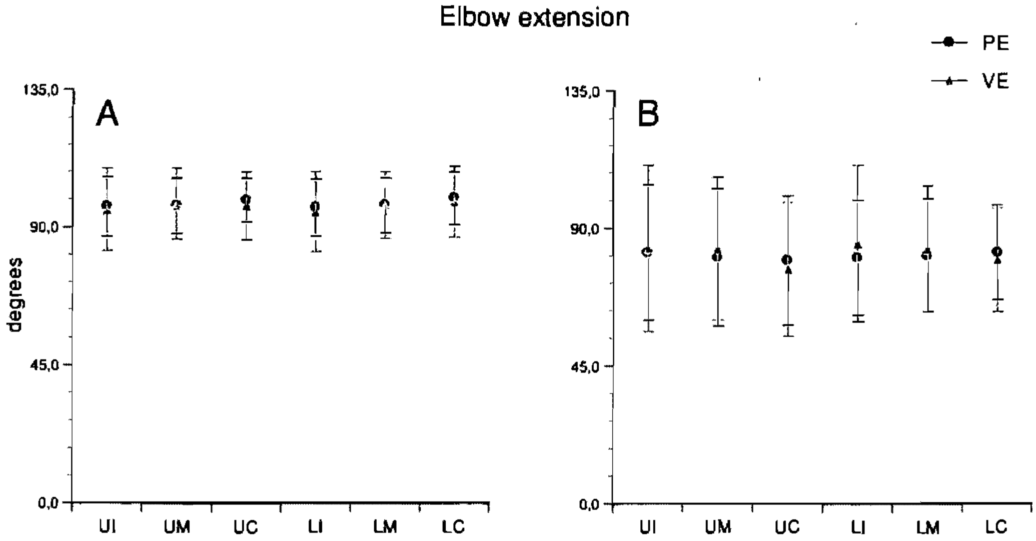
(UI) upper ipsilateral target; (UM) upper middle target; (UC) upper contralateral target; (LI) lower ipsilateral target; (LM) lower middle target; (LC) lower contralateral target. Asterisks indicate significant differences between the environments, (*) $p < 0.05$.

Figure 10. Trunk displacement means and standard deviations of healthy subjects (A) and stroke patients (B) for the 6 targets in physical (PE) and virtual (VE) environments.



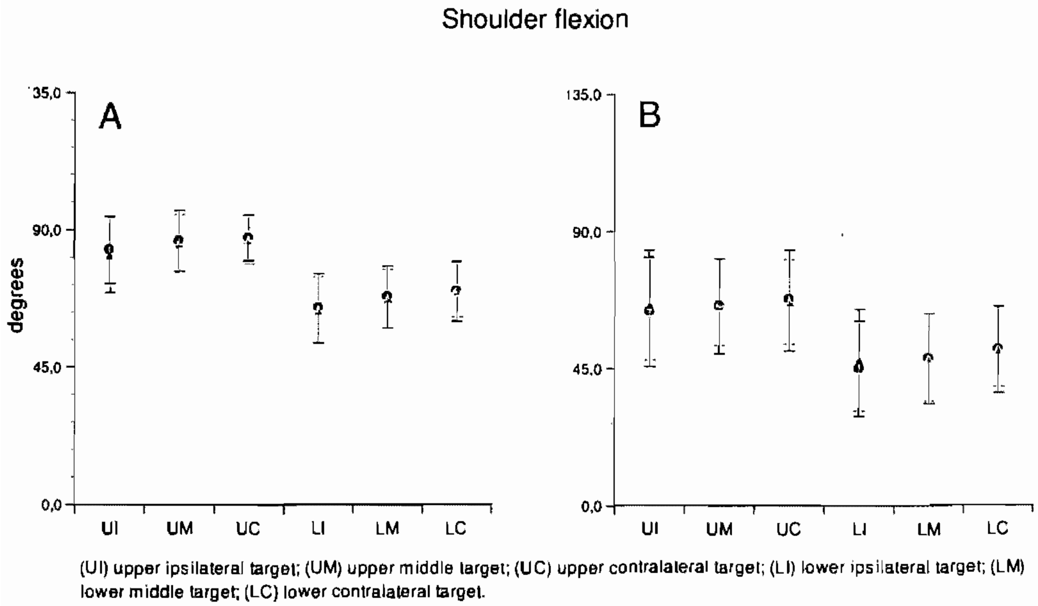
(UI) upper ipsilateral target; (UM) upper middle target; (UC) upper contralateral target; (LI) lower ipsilateral target; (LM) lower middle target; (LC) lower contralateral target. Asterisks indicate significant differences between the environments, (*) $p < 0.05$ and (**) $p < 0.01$.

Figure 11. Trunk rotation means and standard deviations of healthy subjects (A) and stroke patients (B) for the 6 targets in physical (PE) and virtual (VE) environments.



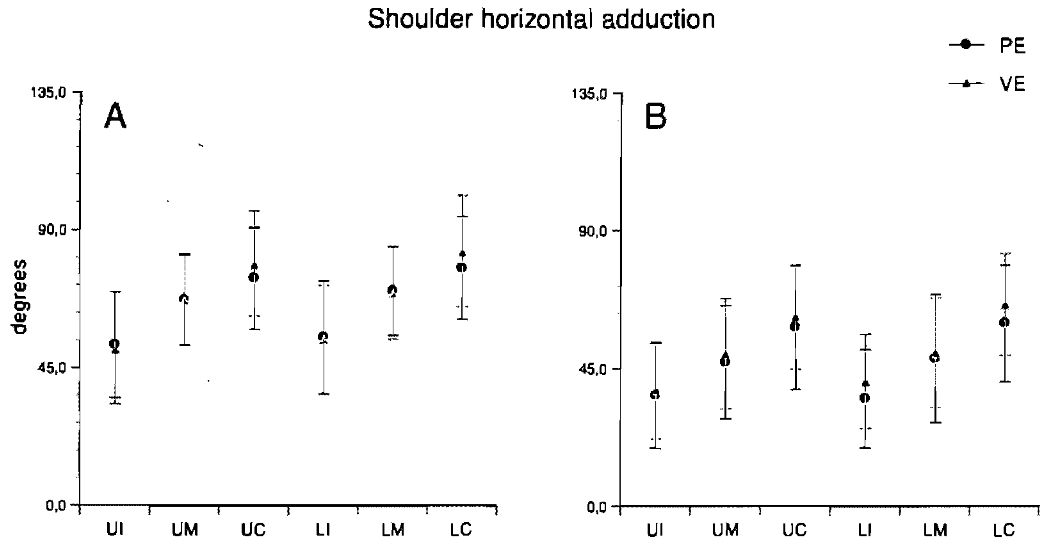
(UI) upper ipsilateral target; (UM) upper middle target; (UC) upper contralateral target; (LI) lower ipsilateral target; (LM) lower middle target; (LC) lower contralateral target.

Figure 12. Elbow extension means and standard deviations of healthy subjects (A) and stroke patients (B) for the 6 targets in physical (PE) and virtual (VE) environments.


Shoulder flexion

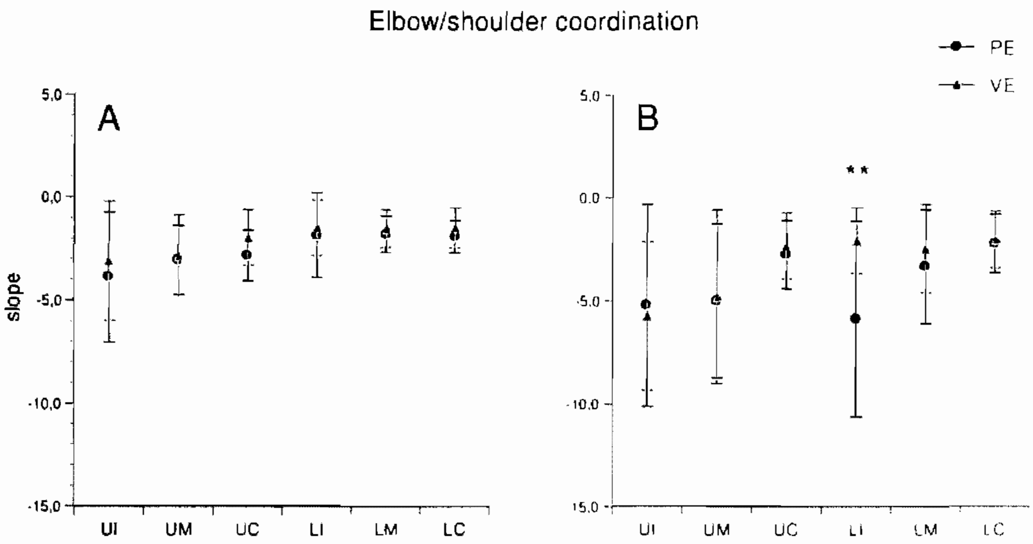
(UI) upper ipsilateral target; (UM) upper middle target; (UC) upper contralateral target; (LI) lower ipsilateral target; (LM) lower middle target; (LC) lower contralateral target.

Figure 13. Shoulder flexion means and standard deviations of healthy subjects (A) and stroke patients (B) for the 6 targets in physical (PE) and virtual (VE) environments.



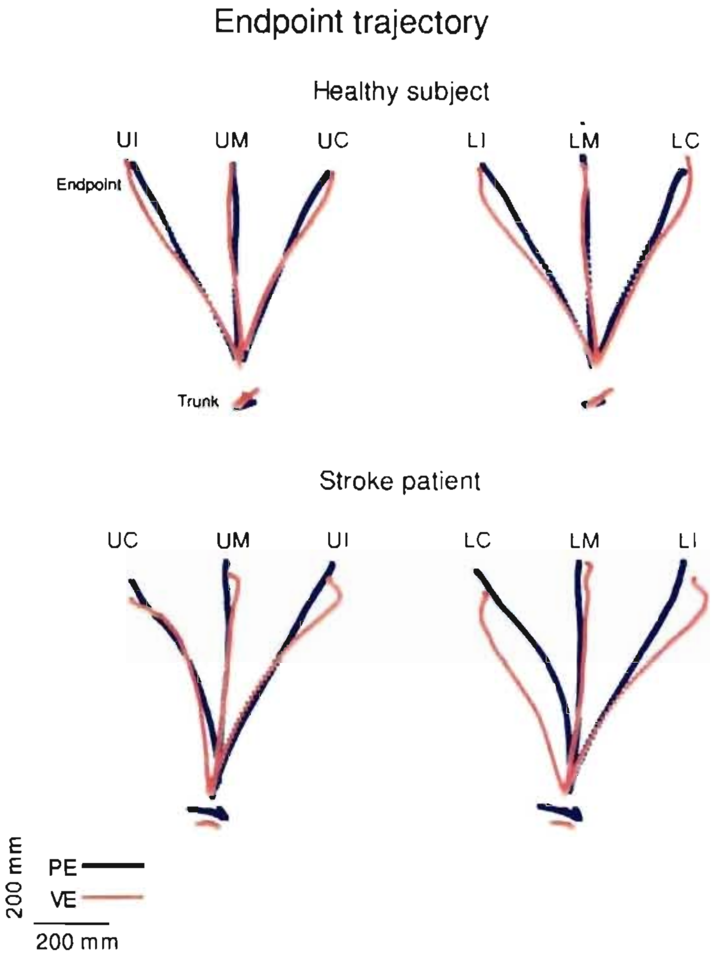
(UI) upper ipsilateral target; (UM) upper middle target; (UC) upper contralateral target; (LI) lower ipsilateral target; (LM) lower middle target; (LC) lower contralateral target.

Figure 14. Shoulder horizontal adduction means and standard deviations of healthy subjects (A) and stroke patients (B) for the 6 targets in physical (PE) and virtual (VE) environments.



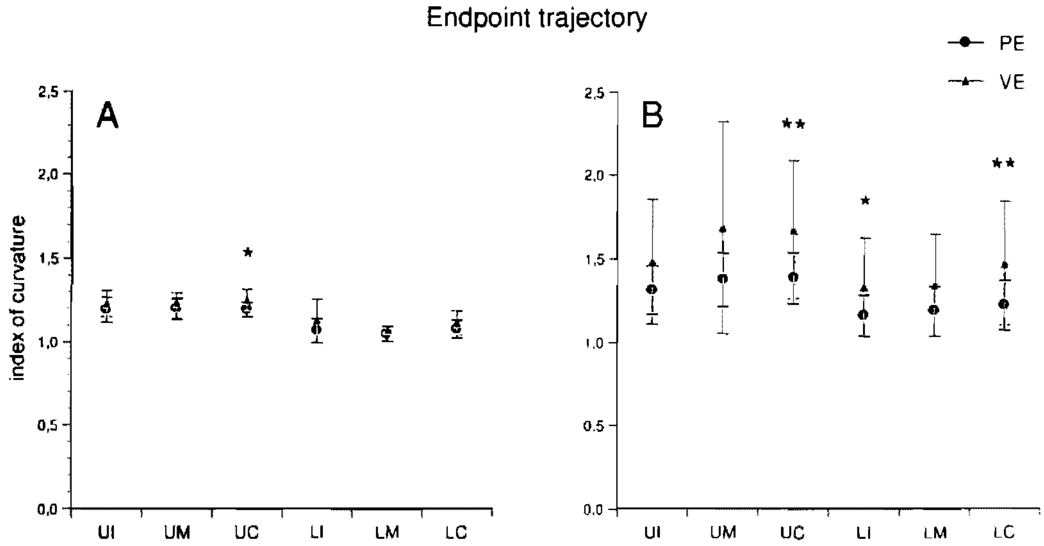
(UI) upper ipsilateral target; (UM) upper middle target; (UC) upper contralateral target; (LI) lower ipsilateral target; (LM) lower middle target; (LC) lower contralateral target. Asterisks indicate significant differences between the environments, (**) $p < 0.01$.

Figure 15. Elbow extension/shoulder horizontal adduction coordination means and standard deviations of healthy subjects (A) and stroke patients (B) for the 6 targets in physical (PE) and virtual (VE) environments.



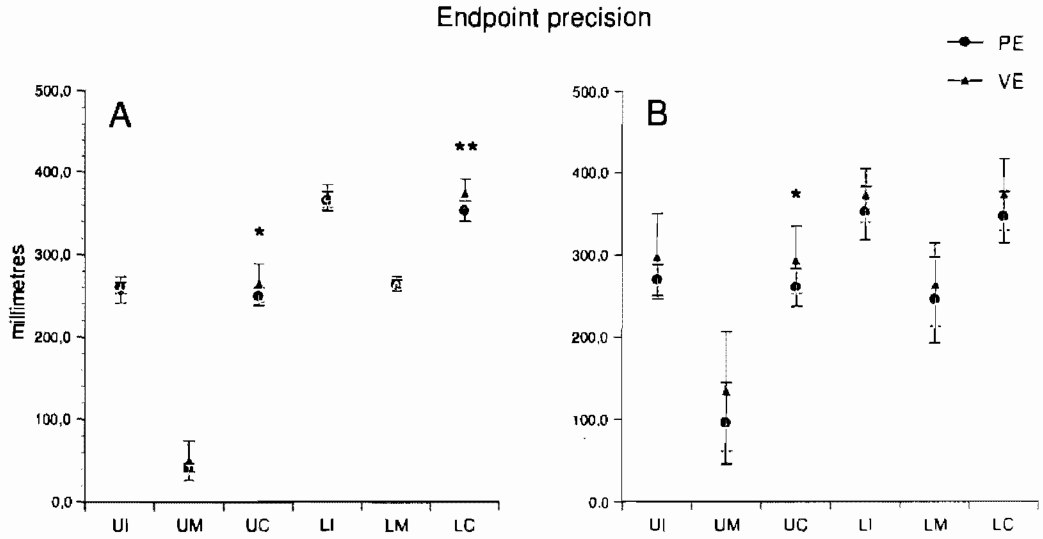
(UI) upper ipsilateral target; (UM) upper middle target; (UC) upper contralateral target; (LI) lower ipsilateral target; (LM) lower middle target; (LC) lower contralateral target.

Figure 16. Mean of the endpoint and trunk trajectories toward the three (3) upper (UI - upper ipsilateral, UM – upper middle and UC – upper contralateral) and three (3) lower (LI – lower ipsilateral, LM – lower middle and LC – lower contralateral) targets in physical (PE) and virtual environments (VE) obtained from 1 healthy subject and 1 stroke patient.



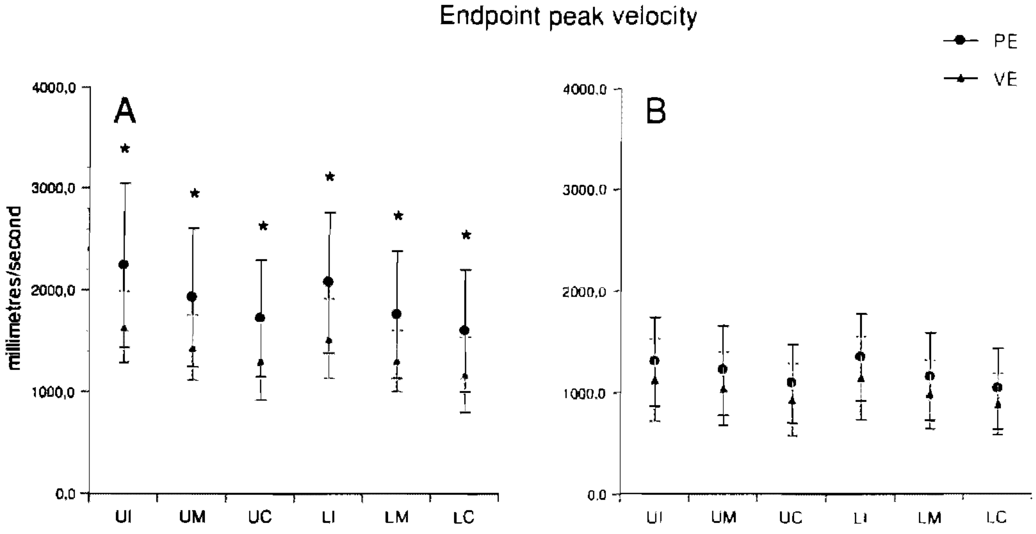
(UI) upper ipsilateral target; (UM) upper middle target; (UC) upper contralateral target; (LI) lower ipsilateral target; (LM) lower middle target; (LC) lower contralateral target. Asterisks indicate significant differences between the environments, (*) $p < 0.05$ and (**) $p < 0.01$.

Figure 17. Endpoint trajectory straightness (index of curvature IC) means and standard deviations of healthy subjects (A) and stroke patients (B) for the 6 targets in physical (PE) and virtual (VE) environments.



(UI) upper ipsilateral target; (UM) upper middle target; (UC) upper contralateral target; (LI) lower ipsilateral target; (LM) lower middle target; (LC) lower contralateral target. Asterisks indicate significant differences between the environments, (*) $p < 0.05$ and (**) $p < 0.01$.

Figure 18. Endpoint precision means and standard deviations of healthy subjects (A) and stroke patients (B) for the 6 targets in physical (PE) and virtual (VE) environments.



(UI) upper ipsilateral target; (UM) upper middle target; (UC) upper contralateral target; (LI) lower ipsilateral target; (LM) lower middle target; (LC) lower contralateral target. Asterisks indicate significant differences between the environments, (*) $p < 0.05$.

Figure 19. Endpoint peak velocity means and standard deviations of healthy subjects (A) and stroke patients (B) for the 6 targets in physical (PE) and virtual (VE) environments.

Stroke patients

As observed in healthy subjects, the interjoint coordination analysis indicated that stroke patients also tended to start the pointing movements using more the shoulder horizontal adduction/abduction than the elbow extension (Figure 9). However, this pattern was less representative than for healthy subjects, corresponding to 88% of the movements in PE and 81% of the movement in VE. Statistically, the coordination between the elbow extension and the shoulder horizontal adduction was similar for all but the lower ipsilateral (LI) target ($p \leq 0.05$) (Figure 15B). For this target, the interjoint coordination in VE had a slope of -2.1 versus -5.9 in PE. The less negative value of the slope suggests that in VE, the pointing movement toward the LI target consisted of a more equal contribution of both joints, while in PE, the elbow extension contribution was greater.

In terms of range of motion from the start to the end of the task, elbow flexion/extension, shoulder flexion/extension and horizontal adduction/abduction were similar in both environments for all targets ($p > 0.05$) (Figures 12B, 13B and 14B, respectively). As well, trunk displacement and rotation during the task were not different in VE and PE for movements to 4 of the 6 targets ($p > 0.05$). Significant differences were observed only for the contralateral targets, where patients moved the trunk less in VE ($p \leq 0.05$) (Figures 10B and 11B).

Conversely to the results in the healthy subject group, the endpoint peak velocity of the movements performed by patients in PE and VE was not different for any target ($p > 0.05$) (Figure 19B). This similarity was also observed for the precision of the movements made toward 5 targets ($p > 0.05$). The UC target was the only target where stroke patients were less accurate in VE than in PE ($p \leq 0.05$) (Figure 18B). Finally, for this group, the trajectory of the endpoint was more curved in VE than in PE for the movements executed to the UC and LC, as well as the LI targets ($p \leq 0.05$) (Figures 16 and 17B). For the other 3 targets, there were no significant differences ($p > 0.05$). A summary of the statistical comparisons between the data from the two environments in the stroke patient group are presented on the Table 2.

Table 2. Comparison (p values) between movements made in the virtual and physical environments of each variable for each target obtained with the multivariate ANOVAs. Significant p values are bolded.

Healthy subjects

Variable	Target					
	UI	UM	UC	LI	LM	LC
Trunk displacement	0.766	0.778	0.386	0.857	0.715	0.179
Trunk rotation	0.866	0.822	0.232	0.932	0.836	0.152
Elbow extension	1.000	0.672	0.787	0.992	0.673	0.988
Shoulder flexion	0.707	0.849	0.915	0.873	0.883	0.835
Shoulder horizontal adduction	0.845	0.983	0.509	0.941	0.900	0.456
Elbow/shoulder coordination	0.528	0.794	0.107	0.616	0.458	0.238
Endpoint trajectory	0.138	0.065	**0.015**	0.128	0.080	0.051
Endpoint precision	0.580	0.227	**0.043**	0.284	0.521	**0.002**
Endpoint peak velocity	**0.026**	**0.033**	**0.045**	**0.025**	**0.033**	**0.044**

Stroke patients

Variable	Target					
	UI	UM	UC	LI	LM	LC
Trunk displacement	0.496	0.262	**0.043**	0.417	0.335	0.011
Trunk rotation	0.317	0.111	**0.012**	0.493	0.412	0.002
Elbow extension	0.925	0.839	0.560	0.932	0.828	0.466
Shoulder flexion	0.741	0.807	0.912	0.637	0.949	0.901
Shoulder horizontal adduction	0.761	0.680	0.604	0.332	0.793	0.357
Elbow/shoulder coordination	0.744	0.887	0.470	**0.006**	0.347	0.714
Endpoint trajectory	0.091	0.058	**0.009**	**0.023**	0.053	0.007
Endpoint precision	0.056	0.098	**0.010**	0.092	0.332	0.058
Endpoint peak velocity	0.249	0.215	0.248	0.183	0.224	0.236

4.2. Presence Questionnaire

As described previously, the participants' degree of agreement with the statements of the Presence Questionnaire was investigated separately for each of the 10 statements. In total, 25 participants (15 stroke patients and 10 healthy subjects) completed the questionnaire. The two first healthy subjects to participate of the experiment did not complete the questionnaire. The frequency of item responses for all statements is summarized in the figure 20. Participants strongly agreed with statements 1, 3, 5 and 9, as demonstrated by the most frequent response (i.e. mode; 8) and the median (8). This indicates that the users: felt accustomed to the VE when the experiment started; thought that the physical hand position was well represented by the blue dot; could recognize the sounds from the VE while they were performing the movements and finally, very much enjoyed practicing in this virtual environment.

Participants also agreed with statements 4, 6, 7, 8 and 10 (Figure 20). For statements 6 and 10, the median score was 7, while for statements 4, 7 and 8, the median indicated a level of agreement equal to 6. These results suggest that users: could estimate the distance between them and the virtual buttons on the wall; believed that the task in the VE was more pleasant for arm movement training than conventional rehabilitation; were comfortable when they wore the HMD; thought that the movements produced in VE were similar to those produced in PE and lastly, were so engaged in trying to successfully complete the task that were unaware of any activity or distractions that occurred around them.

Finally, in contrast to the majority of the statements, the participants did not agree that the quality of the images that they saw made them feel as if they were in an elevator. In fact, even if the median showed a degree of agreement equal to 5, the item most chosen for statement 2 indicated maximal disagreement (1; Figure 20).

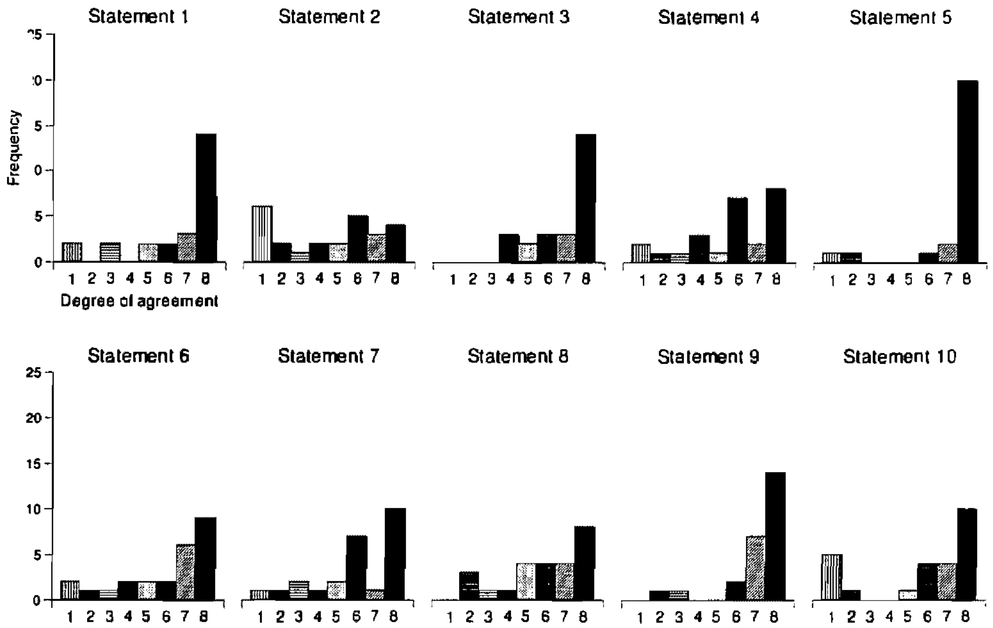


Figure 20. The most frequent responses in the questionnaire obtained from 10 healthy subjects and 15 stroke patients. The least agreement was indicated by response 1, while the most agreement was indicated by response 8.

Chapter 5. Discussion

The present project is an important step in the understanding of the potential of VR systems to be used in research and clinical rehabilitation. Since VR was first mentioned as a potential tool for sensorimotor rehabilitation in the 1990s, authors have investigated its applicability through experimental studies in which, for example, motor improvements are compared in patients training with and without VR (Jang et al. 2005; You et al. 2005). However, the question of similarity between movements made in 3D VE and physical environments has not yet been much investigated. In 1998, Latash expressed some worries about the use of VR in motor rehabilitation. According to him, current knowledge about sensorimotor integration cannot suggest the level of contribution of the different sensory components experienced in VR for voluntary movement production. In fact, even with the technological advances in the VR domain, certain types of haptic feedback are not yet properly delivered in virtual experiences. Because of the lack of development of haptic feedback in VE, we chose a motor task that did not involve haptics as the motor task for our study.

In the present study, although the targets in each environment were similarly arranged, there were some differences in experimental conditions such as whether or not the subject wore the HMD. However, since our goal was to compare the movements done in the VE displayed through an HMD to the same movements executed in the usual clinical situation (i.e. PE), these variables were not directly controlled. Thus, in the virtual condition, participants executed the movements wearing the HMD, while in the physical condition they did not need to wear this apparatus. It is relevant to say that in addition to its approximate 1 kg weight, the HMD reduced the field of view (FOV) of the user to 30° in vertical and 40° in horizontal directions (i.e. 50° in diagonal), while in humans the normal FOV values corresponds roughly to 120° vertically and 180° horizontally (Knapp & Loomis 2004) .

In a previous study, Loftus et al. (2004) observed that reduced FOV (i.e. binocular 4° and 16° FOVs) does not affect distance perception during pointing and reaching movements to objects placed at distances between 20-40 cm. Similarly, Creem-Regehr et al. (2005) and Knapp and Loomis (2004) showed that long distance estimation with restricted FOV was not different to unrestricted FOV condition (i.e. normal). In these cases, subjects had to walk toward targets positioned at 2-15 m from their start position and the FOV ranged from 32° to 43° vertically and from 38° to 47° horizontally. Conversely, Loftus and colleagues also noted in their study that the restricted FOV affected pointing movements in terms of precision, which became more variable, and in terms of peak velocity, which was reduced. Supporting Loftus et al., Gonzalez-Alvarez et al. (2007) also remarked a diminished peak velocity during reaching movement with the FOV restricted (i.e. 11°-23° FOV). Albeit the FOVs investigated in those 2 studies were considerably smaller than the FOV in the HMD of this present study, it can suggest that participants of our study were in a disadvantaged situation when they were wearing the HMD.

Another difference between environmental conditions was that in PE, participants could see their whole UE during the task, while in VE, participants received only visual feedback about the position of their endpoint (finger). However, this difference may not necessarily influence the results, since several studies have shown that vision of the endpoint is most likely used as a reference to guide UE movement (Rossetti et al. 1995; Sergio & Scott 1998; Saunders & Knill 2005; Ketcham et al. 2006).

The results obtained in the present study demonstrated that the same ranges of joint motion used for movements in PE were used in the fully immersive VE by both healthy subjects and stroke patients. This was true for all degrees of freedom investigated and for all directions of movement and levels of difficulty. In addition, in the current study, healthy subjects performed the movements similarly in both environments in terms of elbow/shoulder coordination, trunk displacement and trunk rotation. This suggests that for all movement pattern outcomes, no differences in the healthy subjects' movements were found between the environments.

Similarities in elbow/shoulder interjoint coordination measures recorded for movements executed in VE and PE were previously observed for movements displayed on a 2D computer screen by Viau et al. (2004). This result was supported for the 3D movements investigated in our study, such that participants made pointing movements that required similar contributions from the elbow and shoulder joints in both environments. However, Viau et al. (2004) did observe differences in ROM for movements performed in VE and PE because of difficulties with depth perception due to the 2D virtual environment. In Perani et al. (2001), cortical activation was investigated while the subject observed an object-grasping action in four different environmental conditions: PE, 3D VE with a "realistic" representation of the hand, 3D VE with a coarse representation of the hand, and 2D movie displayed through a TV screen. In all environmental conditions, cortical activation was present in the motor cortex, visual areas, posterior parietal cortex of the left hemisphere and left parietal operculum. However, the 2D condition was the only one in which the inferior temporal regions were not activated. This places 2D VE at a disadvantage compared to 3D VE, since the inferior temporal regions are important for object recognition (Janssen et al. 2000) and responsible for perceptual and cognitive representation of actions. The lack of inferior temporal activation suggests that the observed action may be meaningless for the person (Decety et al. 1997).

Another important factor is that in 2D VE, users cannot take advantage of stereopsis, which is an important binocular cue to provide accurate distance information (Cumming and DeAngelis 2001). Movements such as pointing and reaching, when executed in a 2D VE would necessarily be similar to movements made in conditions of monocular vision (Viau et al. 2004). Even if in some cases (i.e. when some depth cues are present) monocular vision does not affect perceptual distance estimation, binocular depth cues are necessary when relatively fast and skilled movements are required (Servos 2000).

Additionally, in a previous study by Interrante et al. (2006), distance perception in VEs displayed through HMDs was noted to be similar to that perceived in PEs. We could say that our results support this observation since participants used trunk displacement and elbow extension similarly in VE and PE (except for stroke patients' trunk displacement when pointing to contralateral targets). In support of this finding is that participants indicated that they could estimate the distance between them and the virtual targets on the wall in the Presence Questionnaire.

In the PE, pointing movements in stroke patients were done with excessive trunk movements, even though the targets were placed within arm's reach (Cirstea et al. 2003b) In contrast, stroke subjects used less trunk displacement and rotation when pointing to contralateral targets in VE. One factor that may have contributed to this difference was the ergonomic influence of wearing the HMD. When wearing the HMD, participants had an additional weight of 1 kg on their heads. This weight may have restrained the movement of the head and trunk especially when movements to the contralateral targets were made. This was observed only in the stroke group since healthy subjects did not involve trunk movements when executing the task.

Healthy subjects did not always produce the pointing movements similarly in both environments. Similarities in the endpoint trajectory and precision were observed however, for movements toward ipsilateral and middle targets. These results were comparable to those observed in the stroke patients. However, for the patients, the similarities in the endpoint trajectories were observed for movements to middle targets and to one of the ipsilateral targets (i.e. UI target).

Considering the endpoint trajectory, our results support the findings of Viau et al. (2004), in which trajectory curvature was similar in both a PE and a 2D VE when movements were made to a sagittal target corresponding to the middle targets in our study. However, in contrast to the current study, Viau and colleagues did not investigate movements in ipsi- and contralateral directions. In terms of endpoint precision, the similarity in the participants' accuracy when movements were executed toward ipsilateral and middle targets also reinforce the suggestion that distance perception in fully immersive VE and PE are similar.

Nevertheless, when performed toward contralateral targets (i.e. UC and LC), healthy subjects made less accurate and more curved movements in VE compared to PE. This was also seen in movements made by the stroke patients. In terms of peak velocity, healthy subjects but not stroke subjects made slower movements in VE compared to PE for all the 6 targets.

Temporal movement parameters were also investigated by Interrante et al. (2006). In their experiment, subjects walked different distances (i.e. 10, 20 and 30 feet) in PE and VE. Their results showed that subjects walked approximately 2 s slower for all distance conditions when they were immersed in a 3D VE displayed through an HMD compared to walking in the PE. Thus, our findings and those of Interrante et al. (2006) suggest that movements are slower in VEs displayed through an HMD. As previously discussed, a possible cause for speed reduction in VE condition in those 2 studies may be that participants had a reduced field of vision when viewing the environment through the HMD. This conclusion is not true for stroke patients since no differences between their peak velocity in VE and PE were found. The lack of difference may be due to the fact that movement velocity is already diminished in these individuals even in physical environments (Cirstea and Levin 2000).

Differences observed between the environments could also be explained by the differences in perceptual conditions. While 3D VEs have visual perception advantages when compared to 2D VEs, they do not exactly reproduce the visual stimuli obtained from the physical world (Perani et al. 2001). While cortical activation of the right inferior parietal cortex occurs in people when they see a physical hand moving, it does not occur when the same people observe the same movement in VEs. This is relevant since the right inferior parietal cortex is an important area for motor planning (Decety 1996) and plays a crucial role in visually guided reaching and manipulation (Sakata et al. 1997). In addition, as observed by Inoue et al. (1998), the inferior parietal cortex is part of a network formed by the premotor and posterior cingulate cortices, as well as with the cerebellum. These regions are responsible for monitoring self-movements and for integration of visual and proprioceptive information with ongoing motor commands to achieve accurate pointing.

An interesting finding in our study was that differences in kinematics, when present, were usually for movements made toward the contralateral targets. The literature reports that people prefer to use the most proximal hand to the target/object when they execute pointing and reaches (Helbig and Gabbard 2004). This suggests that the movements to the contralateral targets were less natural and may have demanded a higher degree of difficulty.

Finally, the Presence Questionnaire filled out by the participants indicated that they did not have problems in feeling immersed and familiar with the VE, even if they did not think that our VE was similar to a real elevator. In addition, after the kinematic recording, participants were very pleased in perform pointing movements in the VE and they were also ready to continue this task. The results of the questionnaire suggest that use of VEs improved patients' motivation and consequently, their commitment to the training.

In this study, we observed that healthy subjects executed pointing movements slower in the VE displayed through the HMD. Aside from this difference, in general, movements in fully immersive VE and PE were performed similarly by both healthy subjects and stroke patients. Guiding the movement and accuracy in VE was higher when participants pointed towards contralateral targets. In addition, when pointing to contralateral targets, trunk movements in stroke patients may have been limited by wearing the HMD. Future research should verify if differences in movement kinematics exist when more complex movements involving object manipulation are done in fully immersive VEs. If VR environments are to be used as an intervention to improve motor performance of the arm in stroke patients, it would also be necessary to investigate if and how motor learning may be affected by the training environment.

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Annex I. Ethics approval

Comité d'éthique de la recherche
des établissements du CRIR

Certificat d'éthique

Par la présente, le comité d'éthique de la recherche des établissements du CRIR (CÉR) atteste qu'il a évalué, lors de sa réunion du 14 décembre 2005, le projet de recherche **(CRIR-183-1005)** intitulé :

« Cinématique du mouvement de pointage dans les environnements virtuel et physique chez les sujets adultes hémiparétiques».

Présenté par: **Mindy Levin**

Le présent projet répond aux exigences éthiques de notre CÉR. Le Comité autorise donc sa mise en œuvre sur la foi des documents suivants :

- Lettre introductive datée du 12 octobre 2005;
- Formulaire A daté du 17 octobre 2005 ;
- Grille d'évaluation scientifique datée du 3 novembre 2005;
- Document intitulé « Budget du projet »;
- Document intitulé « Budget » ;
- Lettre et formulaire d'évaluation de la convenance institutionnelle du Centre de réadaptation Constance-Lethbridge, datés du 15 novembre 2005, confirmant l'acceptation du projet sur le plan de la convenance institutionnelle ;
- Lettre et formulaire d'évaluation de la convenance institutionnelle de l'Institut de réadaptation de Montréal, datés du 26 novembre 2005, confirmant l'acceptation du projet sur le plan de la convenance institutionnelle ;
- Lettre de l'Hôpital juif de réadaptation, datée du 17 novembre 2005, confirmant l'acceptation du projet sur le plan de la convenance institutionnelle ;
- Protocole de recherche intitulé « Cinématique du mouvement de pointage dans les environnements virtuel et physique chez des sujets adultes hémiparétiques » ;
- Formulaire d'information et de consentement pour votre participation à un projet de recherche-sujets contrôles (version du 17 janvier 2006, tel que datée et approuvée par le CÉR) ;
- Formulaire d'information et de consentement pour votre participation à un projet de recherche-sujets hémiparétiques (version du 17 janvier 2006, tel que datée et approuvée par le CÉR) ;
- Information and Consent Form for Participating in a Research Project for Healthy Subjects (version du 17 janvier 2006, tel que datée et approuvée par le CÉR) ;
- Information and Consent Form for Participating in a Research Project for Patients with Hemiparesis (version du 17 janvier 2006, tel que datée et approuvée par le CÉR) ;
- Questionnaire d'évaluation des environnements virtuels ;

Annex II. Consent form

CR/R
Centre de recherche
interdisciplinaire
en réadaptation
du Montréal métropolitain

Information and Consent Form for Participating in a Research Project

Title of the Project

KINEMATICS OF POINTING MOVEMENTS IN VIRTUAL AND PHYSICAL ENVIRONMENTS IN ADULT WITH HEMIPARESIS

Project Investigators

Mindy Levin, PT, Ph.D. Principal Investigator - Tel: (514) 398-3994
Daniel Bourbonnais, OT, PhD, - Co-investigator - Tel. (514) 340-2111, local 2036
Luiz Alberto Manfré Knaut, PT, M.Sc. Candidate - Tel. (514) 340-2111, local 2098
Center for Interdisciplinary Research in Rehabilitation, Jewish Rehabilitation Hospital, 3205 Place Alton Goldbloom – Chomedey, Laval (Québec), H7V 1R2

Preamble

We are requesting your participation in a research project. However, before agreeing to participate in this research project, please take the time to read, to understand and to carefully consider the following information.

This consent form explains to you the goal of the study, the procedures, the advantages, risks and disadvantages of your participation as well as the people with whom you can communicate when necessary.

The present consent form may contain some words with which you are unfamiliar. We invite you to ask any and all questions that you may have.

Patients with hemiparesis: Kinematics of pointing movements in virtual and physical environments in adults with hemiparesis.

The goal of the study

The main goal of this study is to evaluate the characteristics of arm movements made in a physical environment ("real world" – PE) and in a virtual reality environment (VE) and to verify if these movements are similar in both environments.

Nature of my participation

My participation will include a clinical evaluation session of 30 minutes and an experimental session of 40 minutes (including 15 minutes to prepare the equipment; 10 minutes to evaluate the movements in the PE and 10 minutes to evaluate the movement in the VE with 5 minutes of rest between each) during which the characteristics of the movements of my arm (kinematic evaluation) will be recorded.

During the kinematics evaluation, I will produce pointing movements with my affected arm. The evaluation is divided into two conditions: in a conventional condition of movement evaluation (physical environment), and in a virtual environment condition created by a computer. The experiment will take place at the Motor Control Laboratory at the Jewish Rehabilitation Hospital, in Laval.

The methods used in this study do not pose any serious risks to my health, safety or well being.

Clinical evaluation

The motor function and sensation of my arm will be evaluated. The level of motor function will be evaluated by my capacity to produce selective movements. These evaluations are usually done in clinics by physio- and occupational therapists. The duration of the clinical evaluation is approximately 30 minutes and will not be carried out on the same day as the kinematic evaluation.

Kinematics evaluation

The kinematic evaluation consists of the recording of 144 movements made with each of my arms (72 per condition). In each condition, I will be sitting and the task will be to point towards 6 targets laid out in front of me. For the experiment in the virtual environment, I will wear a pair of glasses attached to a helmet (helmet HMD - Figure 1) that will enable me to look at the virtual environment in 3D and a glove that will reproduce my hand movements in this scenario. Markers will be placed on my arm and my trunk in order to measure my movement patterns using a special camera. The recording of the movements will take approximately 40 minutes.

Patients with hemiparesis – Kinematics of pointing movements in virtual and physical environments in adults with hemiparesis.

Figure 1. Helmet with the glasses which allow visualization of the virtual environment

Personal advantages related to my participation in this research

As this is an experimental study, there is no personal benefit to me as a result of my participation in this study, except that it may advance research concerning treatment interventions for people with stroke.

Personal inconveniences associated with my participation in this research

Feelings of discomfort such as nausea, giddiness, vomiting, headaches, drowsiness and loss of balance can be caused by the use of the HMD helmet. However, the possibility of those problems occurring is very low since the virtual environment will have almost no oscillations and the helmet will be worn for less than 20 minutes during the experiment. Moreover, I will be sitting during the whole experiment so that my balance will not be affected. Finally, I will be questioned during and after the experiment to detect these possible problems.

Information concerning the project

The persons responsible for this project will respond, to my entire satisfaction, to any question that I may have concerning this project in which I accept to participate.

Compensatory indemnity

I will be compensated for my travel expenses to the Jewish rehabilitation hospital (up to a maximum $40), in Laval, for the experiment in the laboratory.

Withdrawing my participation in the study

My participation in this research project is entirely voluntary. I may withdraw from the study at any time and such action will not have any effect on the health services that I am entitled to receive. If I withdraw from the study, the data that concerns me will be destroyed if I so request.

Suspension of the research project by the researchers

The research project may be suspended by the researchers for various reasons or in certain circumstances, for example, future contraindications related to ethics or the establishment of new admission criteria for which my participation is no longer required.

Access to my medical chart

I agree to permit the persons responsible for this project to consult sections of my medical chart directly pertinent to the present research project. Yes ☐ No ☐

Access to my research chart

The current Quebec legislation permits individuals to have access to all data concerning them. Given that research data may not always be easy to interpret, this consultation may be done with a researcher involved in the study.

Confidentiality

All persons associated with this project adhere to the strictest policies of confidentiality. Personal information concerning me (name, address and any other information) will be coded and kept at the Research Centre of the Jewish rehabilitation hospital in a locked filing cabinet accessible only to research personnel. In addition, all data will be kept for a period of 5 years and then destroyed. For the purposes of presentation or publication of the research results or use of the results for teaching purposes, my data will not permit anyone to identify or trace me.

An exception will be made if my chart has to be revised by a research ethics committee or by agencies that support this research. The members of these committees are obliged to respect my confidentiality. In some cases, a tribunal can, when ordained, authorize a third party to consult my research dossier.

Responsibility in the case of an accident

In accepting to participate in this research, I do not renounce my rights nor do I free the researchers, their organizations, businesses or institutions from their professional and legal responsibilities.

Patients with hemiparesis: Kinematics of pointing movements in virtual and physical environments in adults with hemiparesis.

Additional information

If I have any questions about my rights or responsibilities or my participation in this research project, I may contact the coordinator of research ethics for CRIR Me Anik Nolet, at [redacted]

CONSENT

The nature of the research, the procedures used, the risks and the benefits related to my participation in this study as well as the confidential nature of the information that will be gathered during the course of the study has been explained to me.

I have had the opportunity to ask all my questions concerning different aspects of the study and I have received satisfactory answers.

I, the undersigned, agree voluntarily to participate in this study. I may leave the study at any time without any consequences to myself regarding my relationship with my physician and other professionals.

I acknowledge having received a copy of the information and consent form.

Name of participant:	**Signature of participant:**
______________________________	______________________________
Name of investigator:	**Signature of investigator:**
______________________________ (In capital letters)	______________________________

Signed at ________________, on the ______ day of _________, 20____.

Date of preparation of the consent form: January 15, 2006

RESPONSIBILITY OF THE STUDY INVESTIGATORS

I, the undersigned, ______________________________ declare a) that I have described the terms of the present consent form to the participant, b) I have responded to the participant's questions, and c) I have explained that participation in the research project is entirely voluntary and that he or she may withdraw participation at any time.

____

Signature of researcher

Annex III. Informative letter about the project

CRIR
Centre de recherche
interdisciplinaire
en réadaptation

Centre de recherche interdisciplinaire en réadaptation (CRIR)

PROJET DE RECHERCHE

Cinématique du mouvement de pointage dans les environnements virtuel et physique chez les sujets adultes hémiparétiques

Nous recherchons des personnes ayant subi un accident vasculaire cérébral et qui ont une faiblesse d'un coté de leur corps (hémiparésie) pour participer à un projet de recherche concernant les caractéristiques des mouvements du bras dans un environnement de réalité virtuelle. Les informations recueillies par cette étude contribueront à développer de nouvelles approches pour améliorer la récupération des mouvements du bras chez les patients ayant subi un accident vasculaire cérébral. Cette étude pourra aussi contribuer à une meilleure compréhension des mécanismes de récupération du mouvement suite à un accident vasculaire cérébral.

Votre participation comprendra une session d'évaluation clinique d'environ 30 minutes et une session d'évaluation des mouvements faits avec votre bras faible (environ 1 heure). D'abord, dans l'évaluation clinique, un physiothérapeute évaluera la motricité, la sensibilité et la fonctionnalité de votre bras. Ces évaluations son utilisées couramment en clinique par les physiothérapeutes et les ergothérapeutes. Ensuite, vous participerez à une évaluation cinématique en laboratoire, pour évaluer les caractéristiques du mouvement de votre bras. Cette évaluation sera divisée en deux étapes: lors de la première étape, vouz effectuerez des mouvements du bras dans un environnement réel, c'est-à-dire dans une situation semblable à la vie de tous les jours. Vous devrez réaliser des mouvements de pointage vers différentes cibles. Lors de la deuxième étape, vous répéterez les mêmes mouvements, mais cette fois-ci dans un environnement de réalité virtuelle créé par un ordinateur, qui reproduira le scénario réel.

L'expérience se tiendra au site du CRIR à l'Hôpital juif de réadaptation (HJR : 3205, Place Alton Goldbloom - Chomedey, Laval - Québec, H7V 1R2; Tel: (450) 688-9550, poste 4615).

Si vous êtes intéressé(e) à participer à cette étude et souhaitez recevoir de plus amples renseignements, veuillez contacter :

Mindy Levin, pht, Ph.D., Chercheure. Te[redacted]
Luiz Alberto M. Knaut, pht, candidat à la Maîtrise   Tel: [redacted]

Annex IV. Announcements

Participant(e)s recherché(e)s

Cinématique du mouvement de pointage dans les environnements virtuel et physique chez les sujets adultes hémiparétiques

Nous recherchons des sujets contrôles (sains), en bonne santé, pour étudier les mouvements de pointage dans des environnements physique et virtuel dans le but de confirmer l'utilisation de la réalité virtuelle comme un outil fiable dans la réadaptation des personnes qui ont subi un accident vasculaire cérébral

- hommes et femmes âgé(e)s de 18 à 80 ans, en bonne santé
- n'ayant pas de problème orthopédiques, neuromusculaires ou neurologiques au niveau du membre supérieur ou du tronc
- n'ayant pas de douleur au niveau du bras ou du tronc

Lieu: Centre de recherche de l'Hôpital juif de réadaptation (Laval) au rez-de-chaussée (Laboratoire de contrôle moteur)

Durée: Une séance d'expérimentation d'une heure

Responsables: Mindy Levin, pht, PhD
Tel: [redacted]
Luiz Alberto Manfré Knaut, pht, candidat à la maîtrise
Tel: [redacted]

Annex V. Presence questionnaire

Name :__________ Date :__________

Questionnaire Evaluation of Virtual Environments

On a scale from 1 to 8, indicate your degree of agreement (1- not at all & 8- completely) with each of the following assertions.

1. I felt accustomed to the environment when the experiment started.

Not at all							**Completely**
☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8

2. The quality of the images that I saw made me feel as if I was in an elevator.

Not at all							**Completely**
☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8

3. The movement of the virtual hand reproduced the movement of my real hand.

Not at all							**Completely**
☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8

Name :__________Date :__________

4. I could estimate the distance between me and the buttons on the wall.

Not at all							Completely
☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8

5. I was able to recognize the sounds while I was performing the movements.

Not at all							Completely
☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8

6. The activity of performing pointing movements towards virtual buttons of an elevator provides a more pleasant training environment for arm movement.

Not at all							Completely
☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8

7. I was comfortable when I wore the helmet and the glasses.

Not at all							Completely
☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8

Name :__________ Date :__________

8. I felt that the movements produced in the virtual reality training environment were similar to those that I often perform in a physical setting.

Not at all							**Completely**
☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8

9. I enjoyed practicing in the virtual environment and would like to continue the training.

Not at all							**Completely**
☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8

10. I was so engaged in trying to successfully complete the task that I was unaware of any activity or distractions that occurred around me.

Not at all							**Completely**
☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8