Elements: Clinical Design and Evaluation of a Virtual Reality Augmented Workspace for Upper-limb Rehabilitation of Traumatic Brain Injury

A thesis submitted in fulfilment of the requirements for the
degree of Doctor of Philosophy

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February 2010

This thesis is dedicated to my parents Rodney and Dawn, brother Alistair, and partner Annette.

Your support made this possible

Declaration of Authorship

I certify that except where due acknowledgements are made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work carried out since the official commencement date of the approved research program; and any editorial work, paid or unpaid, carried out by a third party is acknowledged. This work received ethics approval from the RMIT University, and Epworth Hospital Human Research Ethics Committees.

Sections of the studies presented in this thesis have been accepted for publication:

- Mumford, N. & Wilson, P., H. (2009). Virtual reality in acquired brain injury upper-limb rehabilitation: Evidence-based evaluation of clinical research. *Brain Injury, 23(3)*, 179–191.
- Mumford, N. Duckworth, J., Thomas, P., R., Shum, D., Williams, G. & Wilson, P. H. (2010). Upper-limb Virtual Rehabilitation for Traumatic Brain Injury: Initial Evaluation of the Elements System. *Brain injury*, 24(5), 780-791.

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Acknowledgements

Firstly, and most significantly, I would like to thank our project leader, and my supervisor A/Prof Peter Wilson for giving me this opportunity, and providing such patient support and guidance throughout the project. I’m indebted to you for your time, effort, and wisdom.

I would also like to thank the other PhD candidates working on the Elements project, Ross Eldridge and Jonathan Duckworth. Our shared interests lead to an immediate friendship and group cohesion that made our collaboration possible, and tasks such as hauling computer gear around the city so much easier. Thank you for introducing me to your fascinating fields of study, without your dedicated and creative work my own would never have been possible.

Sincere thanks also to Dr. Gavin Williams and the other staff at Epworth Hospital for their support. Epworth’s amazing TBI patients and families have also earned my humble thanks, and admiration. Your showed me what motivation and persistence really mean.

Thank you to the other collaborators on the Elements project, A/Prof Pat Thomas, Prof David Shum, Dr. Heiko Rudolph, Mark Guglielmetti, and Raymond Lam. Your contributions were indispensable.

Our project was also funded in part by an Australian Research Council (ARC) Linkage Grant (LP0562622), and Synapse Grant awarded by the Australia Council for the Arts.

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List of Acronyms

Acronym	Definition
ADL	Activities of daily living
AF	Augmented feedback
ANOVA	Analysis of variance
AOTA	American Occupational Therapy Association
ARAT	Action Research Arm Test
BBT	Box and Block Test
BoTXN-A	Botulinum Toxin-A
CAD	Computer-aided design
CIMT	Constraint induced movement therapy
DB	Downs and Black rating scale
EDS	Exponential data smoothing
FIM	Functional Independence Measure
FMA	Fugl-Meyer Assessment of Motor Function
HMD	Head-mounted display
ITE	Individual, Task, Environment model
JT	Jacobson-Truax clinical significance analysis
KR	Knowledge of results
LCF	Levels of cognitive functioning
MAND	McCarron Assessment of Neuromuscular Dysfunction
NFI	Neurobehavioral functioning inventory
NP	Neural plasticity
OI	Operator interface
OT	Occupational therapy
PROM	Passive range of motion
PTA	Posttraumatic amnesia
PWS	Partial weight support
RCI	Reliable change index
ROM	Range of motion
SMTA	Split-middle trend analysis
TBI	Traumatic brain injury
TSI	Time since injury

Acronym	Definition
TUI	Tangible use interface
VE	Virtual environment
VR	Virtual reality

Summary

Traumatic Brain Injury (TBI) refers to cerebral damage caused by external physical force, and results in a range of cognitive, and physical impairments. Accordingly, developing new technologies to further TBI rehabilitation is a central focus of research. One technology that offers significant advantages is Virtual Reality (VR). This thesis describes the design and initial testing of an upper-limb VR-rehabilitation program for TBI (called Elements).

The aims with the Elements system were to create virtual workspaces that were theoretically sound, challenging, and engaging, yet could be tailored to participants' individual needs. The system has both rehabilitation and assessment functions. The rehabilitation package consists of two sets of virtual environments (VEs) viewed on a 1020 mm (44 in.) horizontal LCD monitor. The four goal-based VEs utilise a stimulus-response format, where participants move real objects to cued locations on the screen. The difficulty of these VEs is scaled to place greater requirements on motor planning by varying task constraints (e.g. randomising the presentation order of movement cues). Additional visual and auditory movement feedback is provided in these VEs to facilitate functional movement. In contrast, the three exploratory VEs have no clear 'goal'. Here participants freely (even creatively) interact with these VEs, which encourages them to devise and execute their own motor plans.

For assessment the system automatically tracks movement accuracy, speed, and efficiency during the goal-based VEs. Feedback plots from this data are used to provide participants with knowledge of their results. Participants underwent 12 one-hour sessions of VR-rehabilitation over 4 weeks. Two empirical trials were conducted to assess the system.

Study 1 was a multiple case-study (with 3 participants), and applied an ABA design. Participants were assessed on the system-measured variables and tests of unimanual, and bimanual function over baseline and treatment phases. Participants improved on movement accuracy, efficiency and unimanual function over the treatment period. These improvements were largely maintained in the second baseline phase. Mixed improvement was seen on speed and bimanual coordination. Accordingly, based on these generally positive results, a further larger sample trial was conducted.

Study 2 was a within-groups investigation. Our 9 participants' upper-limb and neurobehavioural function were measured before and after one month of normal therapies alone, and following one month of normal and VR-rehabilitation. Participants demonstrated no significant improvements over the normal rehabilitation period (except for the speed variable). Statistically significant improvements in movement accuracy, speed, efficiency, general upper-limb, and neurobehavioural function (especially memory/attention) followed VR-training.

Chapter 7 presents a discussion on these findings, and their implication for the VR-rehabilitation field, and the application of the ITE model in system design. Possible areas for future research (e.g. inclusion of other patient groups, use of brain imaging technology) are also outlined. It was concluded that the results of these trials provide good initial support for the Elements system, and justify further larger sample studies. These are the necessary next steps in trialling the system, and supporting VR's application in TBI rehabilitation.

CHAPTER 1

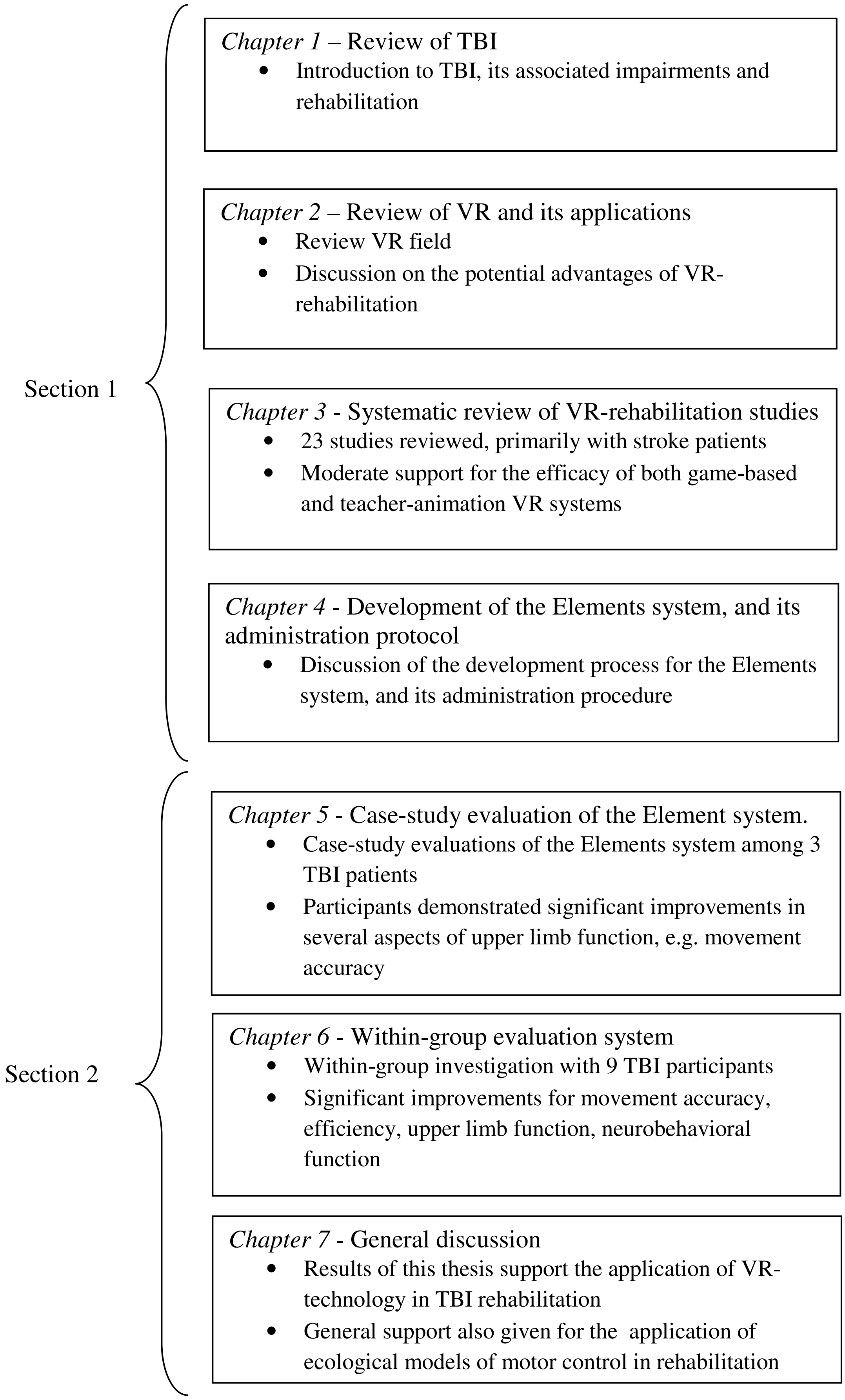
TRAUMATIC BRAIN INJURY CLASSIFICATION AND REHABILITATION

Traumatic brain injury (TBI) refers to cerebral damage caused by external physical force, and results in serious physical and cognitive impairments. TBI has a prevalence of 3%, and typically occurs in young people who require extensive rehabilitation (Nolan, 2005). Indeed, much of TBI research is concerned with the development and efficacy of rehabilitation procedures. One technology that shows great promise for advancing TBI rehabilitation is virtual reality (VR). VR-programs are currently being developed to improve TBI patients' physical abilities, and the cognitive functions that underlie effective movement.

Overview of Thesis

The work presented here was part of a larger collaborative project called the Elements project. The overall aim was to design, create, and test a VR-rehabilitation program (called Elements). This thesis presents my contributions to the broader project. To summarise, my aims were to contribute to the design phase of the project, then conduct the empirical trials. Two other PhD candidates (one from computer engineering, and one from creative media) also contributed to the design of the system, and were responsible for its creation and programming. Their respective publications should be consulted for details on this(Duckworth & Wilson, in press; Duckworth, et al., 2008; Eldridge & Rudolph, 2008; Eldridge, Rudolph, Duckworth, & Wilson, 2007).

This thesis is comprised of two sections. Section one describes the development of the Elements VR-program, including discussion of TBI and VR, a systematic literature review and finally details of the Elements system, and administration protocol. Section two presents the results of two empirical trials of the program among TBI participants. Figure 1.1 illustrates the progression of the thesis chapters.



Section 1

Chapter 1 – Review of TBI

- Introduction to TBI, its associated impairments and rehabilitation

Chapter 2 – Review of VR and its applications

- Review VR field
- Discussion on the potential advantages of VR-rehabilitation

Chapter 3 - Systematic review of VR-rehabilitation studies

- 23 studies reviewed, primarily with stroke patients
- Moderate support for the efficacy of both game-based and teacher-animation VR systems

Chapter 4 - Development of the Elements system, and its administration protocol

- Discussion of the development process for the Elements system, and its administration procedure

Section 2

Chapter 5 - Case-study evaluation of the Element system.

- Case-study evaluations of the Elements system among 3 TBI patients
- Participants demonstrated significant improvements in several aspects of upper limb function, e.g. movement accuracy

Chapter 6 - Within-group evaluation system

- Within-group investigation with 9 TBI participants
- Significant improvements for movement accuracy, efficiency, upper limb function, neurobehavioral function

Chapter 7 - General discussion

- Results of this thesis support the application of VR-technology in TBI rehabilitation
- General support also given for the application of ecological models of motor control in rehabilitation

Figure 1.1. Diagram depicting thesis sections and progression of chapters.

CHAPTER 1: TRAUMATIC BRAIN INJURY CLASSIFICATION AND REHABILITATION

Overview of Chapter 1

The following chapter defines TBI, and discusses its causes and associated impairments. A review of rehabilitation practices follows, with physical rehabilitation described in detail since Elements aimed to promote upper-limb motor control. This chapter highlights that while current practices are effective, TBI rehabilitation remains a progressing field. Thus, emerging technologies are continually developed to supplement existing methods. One that has gained considerable impetus in recent years is VR. In sum, the purpose of this chapter is to introduce the Elements project's target population, and describe the current rehabilitation practices our system was designed to augment.

Traumatic Brain Injury

TBI refers to a cerebral injury caused by external physical force, which results in an altered or diminished state of consciousness, combined with disrupted cognitive and physical functioning (Lefebvre, Pelchat, Seaine, Gelinas, & Levert, 2005). It is estimated that in America 2 million people experience TBI annually. TBI is also responsible for 1 million emergency hospitalisations, and 50,000 deaths a year (Nolan, 2005). The prevalence of TBI in America, the UK, and Australia is estimated at 3% (Lovasik, Kerr, & Alexander, 2001; Nolan, 2005; B. Wilson, 1998). Due to the frequency of TBI, and the extensive rehabilitation required, it is considered one of the most financially burdensome disorders for patients, their family, and the community (Gentleman, 2001). The figure is close to $3 billion per year in Australia alone. This notion is compounded by the fact that TBIs are often avoidable, and are most common among children younger than 5, and males between 16 and 30. Thus, the majority of TBI patients live with their disabilities for most of their lives (Schalock, 1998).

Classification and Causes of TBI

TBIs are classified as penetrating head injuries when an object pierces the brain. Closed head injuries are caused by acceleration and deceleration forces associated with a collision or blow to the head (B. Wilson, 1998). TBIs can also be 'blast' head injuries resulting from an explosion, or lightening strike (Nolan, 2005). Motor vehicle collisions cause 50 per cent of TBIs. Falls, violence, sports-related events, and other accidents account for 21, 12, 10 and seven per cent, respectively (Nolan, 2005). Whatever the cause of TBI, disabilities result from either primary or secondary injuries to the brain.

Primary injuries occur from the contact forces associated with the trauma, or the acceleration forces that follow the initial impact, directly damaging neuronal tissue (Lovasik, et al., 2001). Primary injuries can be either focal - such as contusions, hematomas, and haemorrhages - or diffuse, for example concussion, or diffuse axonal injury (Roth & Farls, 2000). The management and severity of the primary injuries determines the extent of secondary injuries (Lovasik, et al., 2001). These are post-trauma neuronal damage resulting from physiological responses to the primary injury. The most common are cerebral oedema, infection, raised intracranial pressure, and biochemical responses to injury, such as oxidative stress and neurotoxicity (Nolan, 2005). Tissue hypoxia from poor cerebral blood flow can also cause delayed neuronal cell death. These primary and secondary injuries can have long term affects on patients' cognitive, behavioural, social, psychological, and physical functioning.

The severity of TBI (i.e. the extent of patients' injuries, and subsequent disabilities) is rated either on assessment scales (e.g. the Glasgow Coma Scale) or, more commonly, from their length of post-traumatic amnesia (PTA) (Lezak, Howieson, & Loring, 2004). PTA refers to the time period following a TBI when the patient is in a coma, then once conscious is confused, and experience amnesia (Chua, Ng, Yap, & Bok, 2007). TBI severity is classified on the following scale based on length of PTA: < 5 minutes- very mild, 5-60 minutes – mild, 1-24 hours – moderate, 1-7 days – severe, 1-4 weeks – very severe, >4 weeks – extremely severe (Lezak, et al., 2004).

Impairments Associated with TBI

Cognitive Impairments

Reduced attention span and difficulty concentrating are the most frequent cognitive deficits experienced post-TBI (Schalock, 1998). A cross-sectional comparison of 389 TBI patients 5, 10 and 15 years post-injury found minimal improvement in attention and concentration (Engberg & Teasdale, 2004). These are viewed as the most basic cognitive functions and the foundation for higher-order abilities like action planning, problem solving, and response monitoring (Donofrio & Petrucci, 1998). Thus, deficits in attention and concentration are thought to underlie other cognitive impairments.

For example, general processing speed is often greatly impacted. One year after TBI, approximately 25% of patients still experience slowed mental processing (Deb, Lyons, &

Koutzoukis, 1998). Further, in comparison to other cognitive functions (e.g. memory), processing speed recovered slower, and in some cases deteriorated over the first year of TBI recovery, limiting patients' capacity to live independently, and work (Linden, Boschian, Eker, Schalen, & Nordstrom, 2005).

TBI patients experience difficulties at varying levels of memory function. For example, they may not remember past events (retrograde amnesia), or they may be unable to 'manufacture' new memories following the accident (anterograde amnesia) (B. Wilson, 1998). TBI can also disrupt prospective memory (the ability to remember to do something in the future (Shum, Valentine, & Cutmore, 1999)), and working memory (a process for temporarily storing, monitoring and manipulating sensory information), both of which are difficult to rehabilitate, and constrain significantly the ability of young TBI patients' to return to normal intellectual and occupational functioning (Levin, et al., 2004; Schmitter-Edgecombe & Wright, 2004).

Behavioural and Social Impairments

Behavioural problems are less common than cognitive and physical deficits among TBI patients, and are characterised by a marked deviation from their typical behaviour prior to injury (Gentleman, 2001). For example, TBI patients may demonstrate increased risk-taking behaviours. These include substance and alcohol abuse, promiscuity, and violence (Fleminger & Ponsford, 2006; Gentleman, 2001; B. Wilson, 1998). Patients may also develop excessive behaviour patterns, such as swearing, yelling, belligerence, and excitability (Corrigan, Smith-Knapp, & Granger, 1998; Gentleman, 2001; Schalock, 1998). These changes are associated with damage to the frontal, prefrontal, and anterior temporal cortices (Gouick & Gentleman, 2004). Conversely, research has documented apathy, self-neglect, malnourishment, lack of interest in family and friends, and catatonia post TBI (mainly following trauma to the right hemisphere (Gentleman, 2001; Gouick & Gentleman, 2004; Schalock, 1998)). Behavioural changes (especially socially unacceptable ones) can also lead to social isolation (Corrigan, et al., 1998). TBI patients' reduced mobility, physical functioning, and limited cognitive capacity can also facilitate isolation (B. Wilson, 1998).

Psychological Impairments

Approximately 50% of TBI patients meet criteria for clinical depression within one year of their accident. This rate is double that of similar conditions, such as stroke (Gouick & Gentleman, 2004). Depression is particularly common among TBI patients with a history of substance abuse, or who experience social isolation (Schalock, 1998). Research has identified two other significant factors. Firstly, neurochemical changes following damage to the right hemisphere, left basal ganglia, and dorsolateral frontal cortex (see (Gouick & Gentleman, 2004) for review). Secondly, awareness of their functional limitations can reduce patients' life satisfaction, and promote depression (Corrigan, et al., 1998; B. Wilson, 1998). Similar to the general population, TBI patients often experience co-morbid depression and anxiety disorders (B. Wilson, 1998).

As with mood disorders, anxiety disorders in TBI are generally associated with neurochemical imbalances, reduced life satisfaction, and social isolation (Corrigan, et al., 1998). Due to the traumatic nature of TBI, it is estimated that 25% of patients experience posttraumatic stress disorder (PTSD) (Gentleman, 2001; Gouick & Gentleman, 2004). Research has indicated that the intensity of PTSD symptoms is related to the severity of the accident, and, for patients with retrograde amnesia, to 're-experiencing' the event if it is later recalled (Gentleman, 2001). Panic disorder is also common, with 9% of TBI patients meeting diagnostic criteria (Gouick & Gentleman, 2004).

Physical Impairments

The brain centres damaged during TBI often determine the physical disabilities experienced by the patient. For example, damage to the cerebellum may cause gross tremor and staggering gait. Conversely, frontal lobe damage may result in blindness, hearing loss, anosmia, and difficulty initiating movement (Blanton, Porter, Smith, & Wolf, 1999; Gentleman, 2001). Brain stem injury can cause swallowing, and respiratory problems. Furthermore, damage to the primary and secondary motor cortices can result in upper and lower limb dysfunction. These are the most common physical disabilities post TBI (Gentleman, 2001).

Upper-limb deficits include reduced range of motion (ROM), poor timing and accuracy of reaching, and inability to perform fine motor movements. Accordingly, TBI patients have difficulty performing activities of daily living (ADLs), such as hygiene behaviours, eating, and dressing (McCrea, Eng, & Hodgson, 2002). Lower limb impairments manifest as an inability to walk or abnormal gait. For example, they may produce a shuffling gait pattern, experience poor limb coordination, or reduced ROM in hip or ankle joints (Chamberlain, Neumann, & Tennant, 1995). Deficits in upper and lower limb function may also result from medical conditions following the accident. For instance, ossification of soft tissue around the joints can reduce ROM, and make movements painful. The frequent occurrence of hemiplegia can further impair movement coordination, and may result in total loss of sensation in one half of the body (B. Wilson, 1998). These factors highlight the need for prompt physical therapy

Summary

To summarise, TBI is a frequently occurring affliction, most common among young people. TBI results in cognitive deficits including poor attention and concentration, information processing, and memory. Behaviour changes, such as increased risk taking behaviour, and social isolation also occur, which (along with biochemical changes) can facilitate depression and anxiety disorders. However, physical disabilities such as deficits in upper and lower-limb function are the most common. As a result, TBI patients undergo extensive rehabilitation to improve their functioning, and quality of life.

TBI Rehabilitation

In rehabilitation, patients work with therapists to achieve an optimum level of physical, social, psychological and vocational functioning (Bajo & Fleminger, 2002). Accordingly, TBI patients experience a range of therapies, the intensity and focus of which is determined by their level of recovery and individual needs (B. Wilson, 1998). For example, inpatients experience intensive and coordinated physical, cognitive, occupational, and even pharmacological therapies (Cullen, Chundamala, Bayley, & Jutai, 2007). The focus of these is achieving sufficient functioning for discharge. For outpatients, rehabilitation aims to promote function and achieve personal goals, such as return to work/school. This rehabilitation is less intensive, and generally targets physical functioning, and mobility (Chua, et al., 2007). The following discussion will outline the major areas of TBI rehabilitation.

Cognitive Rehabilitation

Cognitive rehabilitation for TBI involves retraining cognitive abilities, and teaching compensatory methods (Comper, Bisschop, Carnide, & Tricco, 2005). This retraining is based on the theory that cognitive functions can be relearned through practice and stimulation (B. Wilson, 1998). Thus, cognitive retraining strategies utilise a developmental approach by targeting basic functions, such as attention and concentration, followed by more complex abilities (Laatsch, Jobe, Sychra, Line, & Blend, 1997). For example, memory rehabilitation would begin with concentration and attention tasks, such as immediately repeating single words spoken by the therapist. Graded memory tasks may follow, for instance immediately repeating a series of three to five words. Finally, they would attempt to remember multiple sentences (B. Wilson, 1998). Teaching patients to compensate for their cognitive deficits is also important for functional recovery. For example, memory deficits are often overcome using reminder notes, diaries, or portable computers (Carney, et al., 1999).

Pharmacological Interventions

Pharmacological interventions are generally used to treat TBI patients' psychological and emotional impairments (Comper, et al., 2005). For example, anti-convulsants, and anti-depressants, have been used to manage mood disorders and agitation (Deb & Crownshaw, 2004). TBI patients have also received Lithium, Neuroleptics, anti-anxiety medications, and beta-blockers to facilitate cognitive and psychological rehabilitation. However, these interventions are not widely used, and the majority of their supporting evidence is based on case-study research. For example, a one month course of Naltrexone, an opioid agonist, significantly improved a 25 year old TBI patient's speech and mobility (Calvanio, et al., 2000).

Pharmacological treatments also manage physical conditions associated with TBI. The most common of these is injecting Botulinum Toxin-A (BoTXN-A) to reduce muscle spasticity (Anwar & Barnes, 2005; Duprey, et al., 2003; Richardson & Thompson, 1999). BoTXN-A is a neuromuscular paralysing agent that produces temporary muscle weakness by inhibiting presynaptic acetylcholine at the neuromuscular junction (see (Anwar & Barnes, 2005; Richardson & Thompson, 1999) for further discussion on this process). During BoTXN-A treatment TBI patients continue physical rehabilitation to strengthen the targeted muscle groups (Anwar & Barnes, 2005). However, despite the popularity of this application, empirical support is limited by lack of sufficient control and sample sizes (see (Duprey, et al., 2003) for review). Accordingly, larger sample clinical trials of BoTXN-A in TBI rehabilitation are a focus for future research.

Occupational Therapy

Occupational therapy (OT) uses purposeful activities to effect health and functional benefits among TBI patients (Marcil, 2007). OT differs from other forms of rehabilitation by being occupation based (in contrast to dealing with specific abilities, e.g. cognitive, or physical). In OT an 'occupation' is considered an important activity performed regularly as part of living a normal life (Hopkins & Smith, 1993). OT interventions are also more subjective and uniquely tailored to the patient than other rehabilitation.

OT conceives a person's daily life to be comprised of five areas: work, self-care, play/leisure, rest, and sleep. Accordingly, the aim is to identify specific aspects (or occupations) in each of these areas that the patient may be functionally limited in, and apply a graded series of tasks to assist them in recovering function. The ultimate goal is to help patients lead a balanced, functional life (Punwar, 1994). As an example, to assist a patient in learning how to dress themself an OT regime may include: remediation tasks such as balance activities to reduce fear of falling while dressing, memory games to assist the patient in remembering the 'steps' to dressing themself, or adaptive methods such as using a checklist for the process (Hopkins & Smith, 1993).

Physical Rehabilitation

Physical Rehabilitation and Motor Control Theory

TBI rehabilitation procedures are the result of ongoing research, and the application of new theories of motor control (i.e. how an individual produces movement (Bate, 1997)). In developing the Elements system, we drew heavily on current theories of motor control. Specifically, our program was based on Ecological theory. The following discussion will introduce the theories of motor control we applied in our design (see Chapter 4 for further discussion).

The application of motor control theory in rehabilitation dates back to the 1950's. And, earlier theories such as *Hierarchical theory* (review (Kawato, Furukawa, & Suzuki, 1987)), *Motor programming* (review (Summers & Anson, 2009)) and *Schema theories* (review (Sherwood & Lee, 2003)) were based on an 'information processing' view of movement (Kawato, et al., 1987; Sherwood & Lee, 2003). Here, action is considered in terms of information flow within the nervous system. Sensory information flows in from outside to be stored and used, then movement commands flow outwards. This concept is based on our knowledge of physiology, information flow in computers, and the behaviour of animals and humans in experimental environments (Bate, 1997). Conversely, the more recent action theories of motor control (*Dynamic systems* and *Ecological theories*, discussed below), stress the contextual, bi-directional interaction between the performer and the action environment in the production of motor movement. Accordingly, action theories were directly applied in the design of our VR-system, as they indicate that varying the action environment will result in new movement synergies, and redevelop motor control (Shumway-Cook & Woollacott, 2007). Indeed, as discussed in Chapter 2, the capacity to tailor the rehabilitation environment to suit the needs of the patient is one of the great advantages of VR-rehabilitation (Rizzo, Schultheis, Kerns, & Mateer, 2004).

Dynamic systems theories view this process as ‘self-organising’, where movement occurs through a balanced interaction between the individual and their environment (Smith & Thelen, 2003). Ecological theory states that functional movement is the result of appropriate interaction with the environment, based on how the individual perceives the actions afforded in that environment (Shumway-Cook & Woollacott, 2007). Thus, the notion of helping TBI patients live their lives by teaching them how to interact with their environment, and promoting functional improvements, became a core goal of rehabilitation (B. Wilson, 1998). This involves training patients in real life settings, and teaching specific functional tasks. For example, learning to perform major life-activities, including self-care, and mobility, ADLs, and instrumental activities, such as taking medication (Schalock, 1998).

The process of refining and developing TBI rehabilitation is ongoing. For instance, the *Individual, Task, Environment* model (ITE model, an extension of Ecological theory) is being increasingly applied (and was the basis for Elements’ design). This model is founded on research presenting movement as an embodied phenomenon, where direct perception-action couplings cause purposeful action (e.g. (Gibson, 1966, 1986; Turvey & Carello, 1981)). Briefly, these theorists posit that perceptual properties of different objects and events are mapped directly to the performer’s action systems. As such, the environment is regarded as intrinsically informative to the performer who has developed sensory systems to make best use of what actions are offered in the environment (referred to as affordances) (Gibson, 1966). Therefore, people need not construct object representations to guide their movement; rather ‘planning’ is implicit in the perception-action cycle. Accordingly, this approach does not draw a distinction between the performer and the natural (i.e. environmental/task) constraints of performance.

These theories have been operationalised for use in structuring rehabilitation programs. Thus, the current version of the ITE model states that movement emerges from an interaction between the individual performer, the action environment, and the task at hand (in OT literature this model is also known as the Person Environment Occupation model). Accordingly, an individual’s ability to meet environmental and task demands determines their functional capability (see (Law, 1996; Law, et al., 1994; McColl, et al., 2003; Newell & Jordan, 2008; Polatajko, 1994; Shumway-Cook & Woollacott, 2007; Strong, et al., 1999) for discussion on the ITE model, and its application in rehabilitation). The components of the

ITE model are themselves comprised of different constraints which contribute to movement production, and in TBI patients, describe the current limitations in movement, as well as provide insight into the design of new contexts for learning (Wilson et al., 2006). Individual constraints can be divided into three sub-components: the action systems (including biomechanical constraints), perceptual systems, and cognitive processes (e.g. attention, memory, and motivation-emotion). Task constraints can be classified according to the specific features of a task that regulate how a movement might unfold. For example they may be categorized by function and intention, locomotion and stability, propulsion (of objects), reception, and orientation with respect to objects, terrain, or events (Davis & Burton, 1991; Law, 1996). Finally, environmental constraints concern both the regulatory features of the movement terrain and object(s), social supports, and background conditions like noise and lighting. This model provides a framework for understanding patients' specific areas of disability, and informs what task and environmental factors should be varied during rehabilitation to effectively retrain functional movement (Law, 1996).

Physical Rehabilitation Practices

Physical disabilities are the most common following TBI, and the patient's level of recovery determines the training they experience. Thus, rating scales are used to assess recovery, and inform rehabilitation. The most common of these is the Levels of Cognitive Functioning (LCF) Scale (O'Sullivan & Schmitz, 2007). This measure has demonstrated adequate reliability and validity for classifying TBI patients' recovery, and directing their physical rehabilitation (see (Kaplan, 2006) for description of the LCF scale, and its application). However, there is no established timetable for progression through these stages. Progression varies based on injury severity, intensity of training, and so on. The following sections will discuss physical rehabilitation at each stage of TBI recovery. It is also noteworthy that these practices have been influenced by medical and pharmacological developments, such as serial casting, and BoTXN-A injections, in addition to theories of motor control (B. Wilson, 1998).

Decreased, or low-level response: LCF I, II, and III. During the early stages of recovery TBI patients are in acute hospital care, then an inpatient facility (O'Sullivan & Schmitz, 2007). At level I patients are unresponsive to stimuli. Level II patients respond inconsistently, often giving the same response to different stimuli. Level III is characterized by patients reacting specifically but inconsistently to stimuli (e.g., sometimes turning their head in the general direction of a sound (Radomski, 2000)).

Physical rehabilitation at these stages involves passive range of motion (PROM) exercises, and sensory stimulation (Mackay, Chapman, & Morgan, 1997). PROM involves manually exercising the patient’s limbs to prevent hypertension, and improve muscle tone (Schmit, Dewald, & Rymer, 2000). During PROM the joint being exercised is supported, the bones above the joint are stabilized, and the limb is moved distal to the joint through its full ROM. Upper-limb exercises involve the shoulder, elbow, or wrist. Since impaired hip and ankle ROM can hinder abilities such as sitting, wheelchair positioning, and ambulation, these joints are a focus for lower limb PROM (O'Sullivan & Schmitz, 2007).

Sensory stimulation is used to increase sensory arousal and elicit movement during early recovery. This procedure involves gradually introducing auditory, olfactory, visual, tactile, kinesthetic, and vestibular stimulation, while monitoring for appropriate responses (Ansell, 1991).

Confused – Agitated level of recovery: LCF IV. Level IV begins when patients recover from PTA, and is characterized by agitation, aggression, and noncompliance resulting from disorientation, and persisting amnesia (Radomski, 2000). Since, at this stage of recovery, motor coordination and patient cooperation are generally limited, therapists attempt to promote endurance through passive and active ROM activities (active ROM tasks require patients to perform ROM exercises unassisted) rather than retraining specific skills (O'Sullivan & Schmitz, 2007).

Confused-inappropriate and confused-appropriate levels of recovery: LCF V and VI. At these levels patients remain confused, but can follow simple commands, permitting more intensive physical training. Numerous compensatory, and restoration procedures are used at these stages (see (O'Sullivan & Schmitz, 2007) for review). However, the two most common are gait training using partial weight support (PWS), and constraint induced movement therapy (CIMT) for upper-limb rehabilitation. This level of recovery is also when basic cognitive therapy and OT regimes are initiated.

During PWS training the patient is suspended in a harness that partially supports their body weight (Platz, Hesse, & Mauritz, 1999). Then, they walk on a treadmill while therapists assist by stabilizing their trunk and hips, directing weight shifting, and leg movements.

Accordingly, the amount of weight supported by the harness is gradually decreased to make walking more challenging (Platz, et al., 1999).

CIMT improves the functionality of the patient’s more-affected hand by immobilizing their preferred hand for a portion of the day (Page & Levine, 2003). Patients may perform rehabilitation exercises during CIMT, or simply wear the constraint during their daily routine. However, the efficacy of this method is still questioned. For example, regimes of CIMT for up to six hours per day over three weeks, and five hours of CIMT, five days a week, over ten weeks have both resulted in significant improvements in upper-limb function (O'Sullivan & Schmitz, 2007; Page & Levine, 2003). Further, a research review concluded that CIMT is not superior to un-restrained intensive training (Krakauer, 2006). CIMT’s generalisability and longitudinal effects were also disputed (Krakauer, 2006). Thus, despite showing promise as an intervention, CIMT still requires further investigation.

Appropriate response levels of recovery: LFC VII and VIII. This stage of recovery begins with out-patient rehabilitation. Physical therapy takes place in a day treatment setting, up to five times a week, with return to the community, and school/work as the primary goals. CIMT and PWS training are continued at this stage of recovery, along with other forms of rehabilitation (cognitive, pharmacological, OT) (O'Sullivan & Schmitz, 2007).

Abnormalities in muscle tone, and resulting spastic hypertonia (spasticity) are also addressed (Mortenson & Eng, 2003). Physical therapy for spasticity uses ROM and strengthening exercises targeting antagonist muscles (often in conjunction with BoTXN-A injections). Another procedure used is serial casting (Mortenson & Eng, 2003). Here the spastic limb is extended, and a combination of cloth and fiberglass casts is applied to keep that position. These are removed after one week, and ROM exercises performed. This procedure is repeated until sufficient gains in ROM are achieved (Childers, Biswas, Petroski, & Merveille, 1999).

Emerging Rehabilitation Practices

Since TBI rehabilitation is a progressing field the majority of research is aimed at developing new methods, and technologies (particularly for the advanced stages of recovery (O'Sullivan & Schmitz, 2007)). A prominent example is VR. Application of this technology has gained considerable impetus recently, as it offers numerous advantages to TBI rehabilitation (Rizzo, et al., 2004). And, VR-rehabilitation programs developed to re-teach

ADLs, improve general upper, or lower limb function, and balance have demonstrated positive preliminary results (see (M. Holden, 2005) for review).

Summary of Chapter 1

This chapter presented an introduction to TBI, including discussion on its definition and causes, impairments, and rehabilitation. The theoretical basis and progression of physical rehabilitation were highlighted, since development of physical (upper-limb) abilities was the focus for the Elements training. Yet, TBI rehabilitation is a developing field, with researchers consistently applying new theories and technologies to augment current methods. VR technology, in particular, is seen to have great potential. Chapter 2 presents an introduction to VR, and discussion on its advantages to TBI rehabilitation. It will show that despite its great potential, improving VR's usability and conducting empirical trials to support its efficacy remain areas for further research.

CHAPTER 2

VIRTUAL REALITY AND REHABILITATION

CHAPTER 2: VIRTUAL REALITY AND REHABILITATION

What is VR?

In this thesis VR is considered a combination of computer/information technology that allows users to interact efficiently with simulated programs in real-time. VR promotes a sense of participation within these virtual environments (VEs), and allows clinicians or researchers to present relevant stimuli imbedded in a meaningful and recognisable context (Riva, 2005; Rizzo, et al., 2004; Spear, 2002). The key components of most VR systems are: a computer with an advanced graphics card allowing fast computation of images, a display device (e.g. computer/TV screens, data projectors, or head-mounted displays (HMDs)), interface hardware for users to interact with the VE (e.g. joystick, or mouse controllers, tracking devices mounted on real objects, or data gloves), and software to drive the system (Spear, 2002).

It should be noted that VR is a broad term, which has been increasingly applied in rehabilitation to describe a variety of interactive computer technologies. Accordingly, there is considerable debate on what constitutes VR (see (Cobb & Sharkey, 2007; Riva, 2002) for discussion). In rehabilitation the definition of VR has grown to encompasses a variety of systems utilising differing levels of immersion, computer augmented feedback, and interface devices (Cobb & Sharkey, 2007). Indeed, the broad scope of VR has enabled the rehabilitation community to apply a range of hardware, multimedia computers, virtual and real environments (Riva, 2002). Therefore, classifying the Elements system as ‘VR’ is in accordance with the range of technologies encompassed by this term in a rehabilitation context.

Background

Though the term VR was coined in the late 1980s, the technology dates back to the 1960s when the first HMD programs were used to show 3D movies, and in military training (Schroeder, 1993). Despite these early developments, it was not until the early 1990s, when computers became more affordable, that VR saw an increase in research and production. Indeed, literature from that time advocates VR as a world changing technology that could be applied in every field. See Bletter (1993) and Schroeder (1993) as examples.

However, prototypes were unable to meet the apparent advantages of VR. The systems of the early 1990s were limited by choppy frame rates, poor graphics resolution, and encumbering, imprecise interface devices (see (Ellis, 1994) for discussion). Thus, disparity between VR users' expectations and what the developers could produce became the main limitation to the field. This issue persists presently (McMenemy & Feruson, 2007). For example, it was proposed that VR would become totally immersive, incorporating high definition HMDs, full body feedback suits, even taste and smell stimuli (Bletter, 1993). These systems have not been produced (McMenemy & Feruson, 2007; Vince, 2004). Nevertheless, VR research has continued, leading to applications in fields such as industrial modelling, vocational training, entertainment and psychotherapy.

Applications of VR

Industrial Modelling

Industrial modelling VR (referred to as computer-aided design (CAD) systems) allows designers to create, and manipulate objects in virtual space (Vince, 2004). CAD programs are applied in fields such as engineering and architecture, and permit users to bypass the conceptual model phase of design (Nowacki, in press). CAD also lets engineers 'stress test' their virtual prototypes by systematically applying forces to the virtual model. The success of CAD has lead to an increase in associated research and production (see the dedicated journal Computer-aided Design as an example). Thus, CAD has progressed to allow increasingly precise industrial design, and testing. For example, automotive engineers have devised a program allowing the production and testing (in virtual space) of components in car transmissions (see (Jing, Xuedao, & Zhenghuan, 2007) for specific parts). This PC-based system allows engineers to combine virtual models of components, then test engine efficiency, and integrity. This process would be costly, time prohibitive, and even dangerous with real prototypes (Jing, et al., 2007). Accordingly, the use of CAD is a major benefit in design industries, and a promising area for future VR research (Vince, 2004).

Entertainment

Entertainment is an extremely lucrative and rapidly progressing area of the VR field. It is estimated that the video game industry generates over $6.5 billion annually (McMenemy & Feruson, 2007). Furthermore, games have been the basis for new interface devices (such as remotes with movement sensors, e.g. the Nintendo WiiMote), display methods (e.g. the Playstation EyeToy), cheaper graphics engines and authoring tools (Vince, 2004). Accordingly, this gaming technology is often applied in practical areas. For example, the Nintendo Wii has recently been used in rehabilitation. Preliminary case studies have used the Wii for movement training in children with cerebral palsy (using the Wii-sports package, which includes boxing, bowling, and baseball games (Borbely, Filler, Huhn, & Guarrera-Bowlby, 2008)). Additionally, the Wii balance board has been used for balance assessment among participants with an intellectual disability (Shih, Shih, & Chiang, 2010) (see (Farrell, 2009) for discussion on the use of the Wii in rehabilitation). The success of these initial trials indicates ‘Wii-habilitation’ is a promising area for future research.

Vocational Training

VR-training has become vital to professions where real-world training is dangerous, expensive, or time consuming. It is commonly used as an adjunct for training pilots, drivers, divers, fire-fighters, and soldiers (David Rose, Brooks, & Rizzo, 2005). For example, it is estimated that the US military spends $4 billion on VR-training and equipment annually (Macedonia, 2002). One of their most advanced systems, the Topscene program, combines aerial and satellite imagery to create a detailed 3D representation of a landscape. This is viewed by pilots on a PC monitor or as an immersive flight simulator to plan and practice missions. Other military training programs include marksmanship courses (soldiers fire weapons with infra-red sensors at a large screen), and tank driving simulations (the interior of a tank is re-created, then a 180 degree monitor displays the terrain). Even a peace-keeping VE has been developed. Here soldiers use a head-set to talk to virtual characters in a mob and attempt to calm them (see (Macedonia, 2002) for a review of military VR-training).

VR has also been used in medicine to plan procedures, train clinicians, and assist surgery (Riva, 2002). In one such application, a system using a PHANToM haptic feedback stylus has been applied to train surgeons (Wang, et al., 2007). This program is viewed on a PC-monitor, and provides force-feedback (through the stylus) to simulate operating on skin, organs, or bone. The system tracks the force, timing and precision of virtual incisions, permitting evaluation by experienced surgeons (Wang, et al., 2007) (see (McCloy & Stone, 2001) for review of VR for training surgeons).

Psychotherapy

Since VR can provide clients with a seemingly real experience in a safe environment, the primary application of VR in psychotherapy has been exposure therapy for PTSD and phobias. For example, VR to treat acrophobia has significantly reduced anxiety and avoidance behaviours (see (Parsons & Rizzo, 2008) for a review and meta-analysis). These programs typically utilise a HMD to promote immersion (necessary for the therapy to be effective), and present VEs simulating high locations, such as a bridge (Emmelkamp, Bruynzeel, Drost, & Vandermast, 2001).

VR has also been used in cognitive therapy to challenge maladaptive thinking, such as body image beliefs in eating disorders (Riva, 2005). This is achieved by presenting participants with VEs related to body image beliefs. For instance, in one VE participants categorise animated human characters into weight categories (participants typically view underweight characters as ‘ideal’) (Riva, Wiederhold, & Molinari, 1998). They are then encouraged to examine their choices, and the therapist guides them in correctly re-assigning the groups (Riva, et al., 1998).

Summary

VR is a form of computer technology that allows users to interact with VEs in real-time. Despite being heralded as a revolutionary technology, the VR field suffered as programs failed to deliver on their potential advantages. Nevertheless, VR has been successfully applied in industrial modelling, entertainment, vocational training, and psychotherapy. Based on these applications, VR is seen as promising tool to for TBI rehabilitation.

VR in TBI Rehabilitation

VR- rehabilitation was first proposed in the early 1990s (Rizzo, et al., 2004). The premise being that if VR can elicit genuine experiences among users, who develop skills from those experiences, then VR may re-teach functional skills (Rizzo, et al., 2004). The advantages of VR-rehabilitation are detailed below.

Practice Potentially Hazardous Behaviour

The goal of TBI rehabilitation is to assist patients in achieving an optimum level of physical, social, psychological and vocational functioning (Bajo & Fleminger, 2002). However, patients may not regain function in some areas due to the potentially hazardous nature of those activities (Schultheis & Rizzo, 2001). For example, a VR driving program would allow these skills to be retaught safely (Schultheis & Mourant, 2001). Similarly, a VR-kitchen simulation has been developed to teach TBI patients safe cooking skills (preparing a can of soup, and a sandwich). This may be difficult normally due to dangerous items in the kitchen (Christiansen, et al., 1998). The VR-kitchen has demonstrated adequate patient usability, however clinical assessment has yet to be conducted (Zhang, et al., 2001; Zhang, et al., 2003). VR can also present situations where mistakes may cause embarrassment, like teaching participants with an intellectual disability which bathroom to use in public places. This advantage remains unexplored in TBI (David Rose, et al., 2005).

Home Rehabilitation

Current rehabilitation procedures require participants to practice their new skills at home. The reduced cost of VR-rehabilitation has made it possible for some TBI patients to have systems at home (Weiss, Rand, Katz, & Kizony, 2004). This makes their 'homework' more efficient, since activities can be precisely replicated (Rizzo, et al., 2004). Additionally, therapists can remotely monitor the amount of homework completed, and performance data (Weiss, et al., 2004). Family members can also participate in the homework process by helping in the VR-activities, and having access to results. A number of VR-programs have been developed for home use. For example, evaluation trials support the efficacy of Piron and colleagues' home VR-system to train upper-limb function (described in detail in Chapter 3) (Piron, et al., 2005; Piron, Tonin, Trivello, Battistin, & Dam, 2004).

Automatic Data Collection

An important aspect of TBI rehabilitation is gathering performance data to monitor patients' improvement. Currently this data is based on observation or task based assessments. These have been criticised for being too subjective, since assessment conditions may vary between rehabilitation facilities (Rizzo, et al., 2004). This is especially true for gait assessments (see (Toro, Nester, & Farren, 2003) for review). Automated data recording using VR may permit accurate comparison of data from different facilities, since assessment conditions would be standardised (M. Holden & Dyar, 2002). This data can also be provided as movement feedback for the patient. For example, task performance, or kinematic data could be recorded, and replayed to highlight specific aspects of performance, and guide future movements (M. Holden & Dyar, 2002).

Increasing Enjoyment and Motivation

To maximise the benefits of rehabilitation, patients must commit to lengthy regimes, typically lasting years (M. Holden, 2005). Perhaps the most common reason patients stop rehabilitation is reduced motivation to persist with the often repetitive exercises (B. Wilson, 1998). Accordingly, VR has the potential to make rehabilitation more enjoyable, and improve patients' motivation (Liebermann, Buchman, & Franks, 2006). Two theories have been proposed to explain this potential advantage. Firstly, research has found young adults to be the largest consumers of commercial computer games. Therefore, TBI patients (typically young adults) should be familiar with VR programs, and engage more readily with them (Rizzo, et al., 2004). Secondly, opiate activity in the areas of the cortex connected to auditory and visual perception is increased by experiences that are novel, fast, and immersive, such as VR. Therefore, these experiences are more pleasurable (Rizzo, et al., 2004).

Increased Control of the Rehabilitation Environment and Tasks

Using VR, therapists can tailor activities and VEs to the patient's needs. For example, when rehabilitating hemiplegia upper-limb exercises could encourage use of both hands, or target the more affected arm without resorting to physical restraints (Rizzo, et al., 2004; Schultheis, Himelstein, & Rizzo, 2002). Further, VEs can be made more realistic by introducing visual and auditory stimuli. For example, a driving simulation may begin with a quiet, empty road, then gradually introduce other vehicles, and background noise as the training progresses (Schultheis & Mourant, 2001). Thus, participants could practice skills amidst normal background stimuli. This practice would better prepare them to perform tasks in the real world, and increase the generalisability of training (Rizzo, et al., 2004).

Provision of AF

Movement feedback is essential for developing motor skills. It provides information about movement success, and guides how movement patterns are altered during performance to achieve goals (M. Holden, 2005). Proprioceptive feedback is provided by the vestibular, and peripheral nervous systems, and relates to limb position, location, orientation and movement (Dobkin, 2004). In contrast, exteroceptive feedback is based on sensory information (e.g. visual and auditory) associated with motor performance (M. Holden, 2005). Typically, proprioceptive feedback is used to guide and monitor the mechanics of movement, and exteroceptive feedback to gauge its success (Liebermann, et al., 2006). However, TBI patients often experience difficulty comprehending proprioceptive feedback. Consequently, they rely on exteroceptive feedback for limb position, and movement information (i.e. information typically gained through proprioceptive feedback) , and to assess movement performance (normal exteroceptive feedback) (Liebermann, et al., 2006).

Due to the level of control over the rehabilitation environment afforded by VR, more detailed movement feedback can be provided (Rizzo, et al., 2004). This may be knowledge of results (KR), or augmented feedback (AF). In this thesis AF is taken to refer to feedback related to how the action was performed (i.e. AF supplements proprioceptive feedback), such as illustrating weight distribution during a walking task (Ranganathan & Newell, 2009). KR, will be used in reference to extra information on the success of the action once it is completed (giving additional exteroceptive feedback) (Chen, 2001). For example, VR-systems could provide visual or auditory effects to indicate whether the task was completed successfully. VR systems may incorporate both AF and KR to improve motor learning (Ranganathan & Newell, 2009). For instance, a participant could copy a teacher-animation (as a form of AF) during a reaching movement, and then receive a score for how closely their movement matched the animation's as KR (see Chapter 3 for discussion on teacher-animation VR-programs).

VR would also allow the provision of targeted movement feedback to assist patients in improving the functions trained by the system. For instance, AF may inform participants on their end-point trajectory during a reaching movement (Piron, et al., 2007), or prompt users to focus their attention externally on the effects of their actions, rather than on the movement itself (this can significantly improve TBI patients' functional recovery, see (Wulf & Prinz, 2001) for discussion). Further, summary KR can be given to inform participants of their ongoing performance, and improve their motivation.

Development of Enriched Rehabilitation Environments

Related to AF is the theory of environmental enrichment. An 'enriched' rehabilitation environment is one that not only promotes motor skill acquisition, but engages an individual's attention and imagination. For example, an environment may be enriched by incorporating novel visual or auditory stimuli, and even social interaction (Puurunen & Sivenius, 2002). Research has indicated that enriched environment training facilitates motor learning (Biernaskie & Corbett, 2001), and can significantly improve TBI patients' functional skills (Semlyen, Summers, & Barnes, 1998; Ward, 2005). Accordingly, VR-training programs may incorporate visual, auditory, and even physical stimuli to create an enriched environment. It should be noted, however, that too much or irrelevant stimuli may be distracting, and inhibit performance (see (Puurunen & Sivenius, 2002) for discussion and review). Thus, VR developers must ensure that environmental enrichment is used judiciously, and is task relevant.

Implementation of VR-rehabilitation

VR-technology affords numerous advantages to TBI rehabilitation. However, two issues need to be addressed if this technology is to find broad appeal. The first relates to VR-rehabilitation's usability. Studies addressing usability among stroke patients have yielded positive results. For example, the Rutgers group's (Adamovich, et al., 2004; Boian, et al., 2002; Jack, et al., 2001; Kuttuva, et al., 2006) VR systems were deemed easy to use and enjoyable based on observation, and reports from stroke participants (see (Christiansen, et al., 1998; Pridmore, Hilton, Green, Eastgate, & Cobb, 2004) in addition). Conversely, research on clinician usability has not been positive. For instance, physiotherapists assessing a VR program to develop reaching skill found setting up, and explaining the system took longer than performing real world tasks (Pierce, Mayer, & Whyte, 2001). However, these clinicians agreed that VR-rehabilitation was theoretically sound (see (Edmans, et al., 2004; Lee, et al., 2003) as further examples). Accordingly, improving clinician usability is a priority for future developers.

The second issue is whether sufficient empirical evidence exists demonstrating VR's benefits for patients (Henderson, Korner-Bittensky, & Levin, 2007). Indeed, the notion of evidence-based practice places an expectation upon therapists to use treatments that have the greatest potential for recovery. Without empirical support, it is difficult to justify the time and cost of administering alternative treatments (whether VR or non-VR based). Thus, improving the quality of evidence supporting VR-rehabilitation is necessary to substantiate its potential advantages, and justify its inclusion in TBI rehabilitation.

Summary of Chapter 2

Chapter 2 introduced the VR field. It discussed VR's development, and reviewed previous applications (industrial modelling, entertainment, vocational training, and psychotherapy). The technology's potential advantages to rehabilitation were also detailed. For example, VR allows greater control over the rehabilitation environment, automatic data collection, and provision of AF. However, despite these advantages there remain limitations to VR-rehabilitation. For example, patient usability reports have been positive (e.g. (Adamovich, et al., 2004; Christiansen, et al., 1998)), yet clinicians have found the technology difficult to use (e.g. (Edmans, et al., 2004; Pierce, et al., 2001)). The quality of empirical support for VR-rehabilitation has also been questioned (Henderson, et al., 2007). Thus, to formally assess research trialling VR-rehabilitation, and inform the design of the Elements system, a critical literature review was conducted. This review is presented in

Chapter 3. It demonstrates that current research provides moderate support for VR-rehabilitation.

CHAPTER 3

SYSTMEATIC REVIEW OF UPPER-LIMB VR-REHABILITATION RESEARCH

CHAPTER 3: SYSTMEATIC REVIEW OF UPPER-LIMB VR-REHABILITATION RESEARCH

Overview of Chapter 3

As discussed in Chapter 2, VR affords numerous benefits to TBI rehabilitation. However, VR has not completely delivered on its potential advantages (McMenemy & Feruson, 2007). The current literature on VR-rehabilitation has been discussed in several narrative reviews (Burdea, 2003; M. Holden, 2005; Rizzo, et al., 2004; David Rose, et al., 2005; Schultheis & Rizzo, 2001). These reviews have not critically evaluated the literature. Rather, they have largely adopted a descriptive approach, outlining the broad advantages of VR and the different ways it has been used in rehabilitation. The consensus from these papers is that, once implemented successfully, VR will greatly advance rehabilitation. However, in their critical review, Henderson and colleagues (2007) questioned this conclusion. They identified limitations in the design of VR-rehabilitation studies – including, lack of randomised controlled trials, and no stratification of participant groups. However, this review focused only on stroke patients and covered six studies. Henderson et al. (2007) also included the PEDro scale to assess methodological quality in their review. While this is an established rating scale, it is designed to assess large sample trials. Since VR-rehabilitation is a developing field, most studies are likely to be small sample. Therefore, a comprehensive systematic review, based on a rating scale appropriate to large and small sample studies, both stroke- and TBI-related, was necessary to inform the development of the Elements system, and its subsequent trials. This chapter aims to review previous VR-rehabilitation systems, and assess the quality of evidence supporting VR-rehabilitation using Cochrane-style systematic review. This review demonstrates that despite VR-rehabilitation's promise, only moderate empirical support exists for the technology. Specifically, deficits in internal and external validity were identified as the main limitations to the current research. This review has appeared in published form (Mumford & Wilson, 2009).

Objectives of Review

Despite the numerous potential advantages to TBI rehabilitation afforded by VR, to date research has largely been conducted on stroke participants (see (M. Holden, 2005) for review). Since stroke and TBI share many similarities in disability and rehabilitation (Platz, et al., 1999) the first aim of this review was to describe the research evaluating upper-limb

VR-rehabilitation among stroke and TBI populations. The second aim was to establish the quality of this research using a standardised rating scale—the Downs and Black (DB) scale.

Methods of Review

Search Methods for Identification of Studies

Electronic Databases

The following electronic databases and academic search engines were most recently searched in June 2008: ScienceDirect, ProQuest, Wiley Interscience, PsychInfo, MEDLINE; PubMed, EBSCOHost (which included the CINAHL database), PEDro, Cochrane and Google Scholar.

The following search terms were used (searches were limited to English language articles):

(1) Technology-related terms: Virtual Reality, Augmented Reality, Mixed Reality, tele-rehabilitation, simulation, computerised.

(2) Diagnostic: Acquired brain injury/ABI, stroke, traumatic brain injury/TBI, head injury/closed head injury, head trauma, brain damage/lesion/wound/injury, skull fracture, accident, car accident/collision, cerebral aneurysm, thrombosis, embolism, cerebrovascular accident, anoxia, concussion, hemiplegia, hemiparesis.

(3) Treatment: Rehabilitation, intervention, therapy, activities of daily living/ADL, upper-limb/arm function, reaching, virtual rehabilitation, neuro-rehabilitation, occupational therapy, physical therapy/rehabilitation, neuromotor, coordination, dexterity.

Initially, titles were searched using combinations of terms from each category above. As well, combinations of terms from two of the three categories were title searched. Following an initial search, the names of authors who published relevant papers were also used for key-word searches.

Other Sources

The reference lists from relevant articles were used to identify other papers and authors. Furthermore, journals that frequently publish relevant articles were hand searched: *Brain Injury*, *Cyberpsychology and Behaviour*, *Presence*, *Journal of NeuroEngineering and Rehabilitation, Neurorehabilitation, Archives of Physical Medicine and Rehabilitation, Journal of Head Trauma Rehabilitation, The American Journal of Occupational Therapy and Assistive Technology*. Web-based engines (Google, Yahoo) were also searched for published conference proceedings in the field. The following search terms were added: conference, proceedings, IEEE.

Selection Criteria

During the literature search, articles were identified as potentially relevant based on the inclusion of searched terms in their title. The abstracts of these articles were then read and, if necessary, full-text versions were acquired. The selection criteria used to identify relevant articles are discussed below.

Intervention Research

All studies that aimed to use and evaluate VR-rehabilitation to improve upper-limb function among stroke or TBI patients were reviewed. This search included randomised controlled trials (RCT), pre-post test trials, small-*n* studies, and case studies. Only articles that evaluated the benefits of VR by comparing participants' function before and after treatment were included. Thus, papers that merely proposed the use of VR-therapies, or described the theoretical and design details of such programs were not reviewed.

Participant group. Only studies that included participants recovering from either stroke or TBI were reviewed.

Type of intervention. Selected intervention studies were those using VR-systems designed to improve upper-limb function. Therefore, articles that only described VR-programs, tested robotics systems without accompanying VR-training, or trialed VR-assessment (but not therapeutic) programs, were not included.

Types of outcome measure. Due to the inclusion of RCTs and case-studies in this review, and the focus on upper-limb function, any measure of movement control, learning or skill was deemed appropriate as an outcome measure.

Assessment of Methodological Quality

The DB rating scale (Downs & Black, 1998) was used to assess the methodological quality of the studies reviewed. This scale was chosen since it can be used for both RCT and case-study research (the central factor in selecting the DB scale over more popular ones, such as the PEDro scale), and has sound psychometric properties. The DB scale consists of 27 items (full information can be found in (Downs & Black, 1998)). An example item: 'Is the hypothesis/aim/objective of the study clearly described?' For each item on the scale, a study scored one if it met the criterion, or zero if it did not, or it was unclear. Some items were weighted higher and were scored on a three to five point scale. The maximum score for the DB scale is 31, with higher scores denoting better methodological quality. The DB scale is also broken down into five sub-scales: Reporting (whether sufficient information was provided to permit a full evaluation of the findings), External validity (whether the results can be confidently generalised to the wider population), Bias (whether precautions were taken to prevent bias in the way interventions were administered and measurement of outcomes), Internal validity/Confounding (whether any bias is present in the selection and distribution of participants for the study), and Power (whether the negative findings from a study could be due to chance, based on sample size).

The DB scale has adequate reliability and validity. Significant internal consistency was demonstrated, $KR_{20} = .89$. The test-retest and inter-rater reliability, assessed over a two-week interval were also significant ($r = .88$, and .75 respectively) (Downs & Black, 1998). The DB scale items were developed in consultation with epidemiologists and medical statisticians, demonstrating its face validity. Finally, the scale's criterion validity was verified by its high correlation with the Standards of Reporting Trials Group checklist, $r = .90$.

It took between 10 and 25 minutes to score each article. The scores generated by the DB scale was interpreted using the following criteria; scores > 20 were 'good'; between 11 and 20 were 'moderate', and those < 11 were 'poor' (Hartling, Brison, Crumley, Klassen, & Pickett, 2004). The included studies were assessed by two raters, who independently scored each article, and then compared their results. In the case of discrepancies of three or more points, both raters together reassessed the articles, and the scores were discussed until a consensus was reached.

Evaluation of Control Procedures

It should be noted that the DB scale does not evaluate the control procedures used in a study. However, since control procedures bear on the quality of results, this information was included in the results tables and discussion.

Results

Descriptive Results of Search

The search yielded 23 articles for review. Despite targeting both TBI and stroke research, 22 studies meeting the selection criteria were conducted among stroke patients. One study used 'acquired brain injury patients', the specific injuries experienced by participants were not detailed (M. Holden, Dettwiler, Dyar, Niemann, & Bizzi, 2001). However, the age range of these participants (16-37 years) would suggest TBI, rather than stroke. The majority (15) of research used small-sample or case-study designs, and was typically conducted at a university or hospital. However, many studies did not specify their research setting (e.g. (Gaggioli, Meneghini, Morganti, Alcaniz, & Riva, 2006)). The total number of participants in each study ranged from one to 50, with a mean of 11. Exact descriptive age data could not be calculated due to several papers not providing sufficient age information (for example (Montagner, et al., 2007; Piron, et al., 2003; Yeh, et al., 2007)). The mean age calculated from the 10 studies with sufficient information was 58 years (*SD* 7.1). For the full complement of studies, the mean age was estimated at closer to 50 years.

Results for all Studies Based on DB Ratings

Table 2.1 details the overall and sub-scale DB scores for the reviewed studies. The average DB score was in the moderate range. Table 2.2 contains the number of articles published by year, and their corresponding DB score means, and ranges.

Table 3.1.

DB scores and percentages for all reviewed articles.

DB Sub-scale	DB sub-scale score (mean score/ possible total)	% Score
Reporting	5.8/10	58%
External validity	0.27/3	9%
Bias	3.95/7	56.4%
Internal validity/ Confounding	0.8/6	13%
Power	3.1/5	62%
Total	13.9/ 31	44.8%

Table 3.2.

Number of relevant articles published by year, and their corresponding DB scores.

Year	Number of articles	DB score range	DB mean
1999	1	10	10
2000	0	-	-
2001	3	9-14	11.7
2002	2	9-19	14
2003	1	15	15
2004	3	10-15	12.7
2005	2	19-23	21
2006	2	7-9	8
2007	8	9-22	16
2008	1	13	13

Effectiveness of VR-rehabilitation in the Treatment of Upper-limb Function

Studies concerned with rehabilitation of arm function fell into two distinct types: the first were interventions based on game-like VR programs, and the second were based on teacher-animation (where participants copy a movement demonstrated by a virtual tutor embedded within the VE). A brief description of each VR system has been included in the results tables to provide information on the types of activities patients engaged in during therapy. However, the individual articles or descriptive reviews (Gaggioli, et al., 2006; Hartling, et al., 2004; Henderson, et al., 2007; M. Holden, Dettwiler, et al., 2001; Schultheis & Rizzo, 2001) should be consulted for further details.

Game-like system results. In line with the prevailing assumption of researchers (that VR will make rehabilitation enjoyable, and improve patients' motivation for therapy) many programs make judicious use of (video) game-like interactivity to develop arm function. These systems required participants to use motor movements to interact with a novel and engaging VE, and achieve an outcome goal relative to the context of the game. For example, one of the four tasks tested in the Rutgers group studies (Adamovich, et al., 2004; Boian, et al., 2002; Jack, et al., 2001; Kuttuva, et al., 2006) required the participant to close their fist as quickly as possible to "scare away" a butterfly. In another, participants moved their hand across the flat display to wipe the screen clear and reveal an image. These activities targeted hand strength, speed, ROM, and finger fractionation (Adamovich, et al., 2004; Boian, et al., 2002; Jack, et al., 2001; Kuttuva, et al., 2006). Other studies required participants to reach and touch targets in the VE (Subramanian, Knaut, Beaudoin, & Levin, 2007; Yeh, et al., 2007). For example, in one system (Yeh, et al., 2007) participants had to reach to touch coloured squares seen in the VE. Alternatively, participants in Broeren et al.'s (2004) study used a haptic feedback stylus to hit a ball in the VE against a wall of bricks. The goal was to volley the ball against the wall to remove the bricks, and reveal a picture. A later study used a similar stylus interface device (Broeren, et al., 2008), however the goal was to reach to push circular buttons seen in the VE as quickly and accurately as possible.

Of those studies that employed game-like designs, seven would, statistically, be considered small-*n* and two large sample studies (Howell, 2002) (see Table 2.3 for references). However, sample sizes of 15 and 29 may not be considered large in all research fields, and larger samples are a priority for future VR-therapy research. All studies involved stroke patients. Four of these articles were from a group at Rutgers University and investigated the same technology (Adamovich, et al., 2004; Boian, et al., 2002; Jack, et al., 2001; Kuttuva, et al., 2006). The mean DB score for the game-like systems was 12.6, indicating moderate support. Table 2.3 shows individual DB scores and study details.

Table 3.3.

Details for studies aiming to improve upper-limb function using game-like VR systems.

	Description of VR system: Interface device & workspace	Severity of ABI, and any clinical measures*	Recruitment procedures	Control groups used	Outcome variables*	Duration of intervention	Statistical analyses	Results of intervention	DB score
(Adamovich, et al., 2004)	4 VR tasks, viewed on a flat PC-monitor. Tasks 1-3 (below) use a data glove interface device. Task 4 uses Rutgers Master II glove, which has force resisters attached to each finger. Task 1: move hand from side to side to 'wipe clear' a window and reveal a picture. Task 2: close fist to scare away a butterfly. Task 3: move fingers to play a 'virtual piano'. Task 4: move fingers at set strength.	Left hemisphere stroke occurring > 1 year post stroke	8 stroke patients, no recruitment info.	None	JTAF, Range of motion (ROM), finger fractionation, speed, hand strength (measured by system)	13 days	*t*-tests, ANOVA, between pre-post test data	Significant improvements for 6 participants in ROM, 7 in finger fractionation, 4 in speed, and 3 in strength. Significant improvements in JTAF	15
(Boian, et al., 2002)	Same system as Adamovich et al., 2004	Right hemiplegic stroke, 1-4 yrs post stroke	4 stroke patients, no recruitment info.	None	JTAF, Range of motion (ROM), finger fractionation, speed, hand	3 weeks, 5 sessions per week	None, percentage improvements pre-post test reported.	3 participants improved ROM, finger speed. Four participants improved fractionation. Two	9

					strength (measured by system)			participants improved in JTAF	
(Broeren, Rydmark, & Sunnerhagen, 2004)	VE viewed on a PC-monitor through 3D glasses. Patient uses a haptic feedback stylus as the interface device. VR task: volley a ball back and forth, removing bricks at the back of the VE, and reveal a picture.	Right side stroke, > 12 weeks post stroke	1 stroke patient, no recruitment info.	None	PPT, hand strength	4 weeks, 12 90-minute sessions	None, raw pre-post test scores presented	Improvements in PPT, and hand strength	10
(Broeren, et al., 2008)	VE viewed on a PC-monitor through 3D glasses. Patient uses a haptic feedback stylus as interface device. 6 VEs each containing a point and click task.	Stroke, 1-140 months post stroke	29 stroke patients, no recruitment information	Stroke group, and healthy control group	Hand speed, accuracy and hand path ratio (measured by system)	No details provided	None, results were verbally described, one box and whisker plot provided	Patients scores on all variables were said improve. Comparison with control group not detailed, and magnitude of improvement not supplied	13
(Fischer, et al., 2007)	VE viewed through a head mounted display. Data glove used as the interface device. VR task: to reach and grasp 3D objects seen in the VE.	Stroke, 1 year post stroke, FMA and CMSA scores pre-test	15 stroke patients, volunteers, source unknown	3 groups, cable orthosis, pneumatic orthosis, control	Hand ROM and strength, task performance, FMA, WMT, BBT, RLA.	6 weeks, 1hr session 3 times per week	ANOVA between groups pre-post test	Treatment groups significantly improved in WMF. No significant improvements in RLA, ROM, FMA, BBT strength, task performance.	20
(Jack, et al., 2001)	Same system as Adamovich et al.,	Left hemispheric	3 stroke patients, no	None	Range of motion	9 60-90 minute	None, raw scores pre-post	All participants improved across all	12

	2004	stroke, 3-6 years post stroke. FMA, JTAF scores pre-treatment	recruitment info.		(ROM), finger fractionation, speed, hand strength	sessions	test provided	variables	
(Jang, et al., 2005)/ (You, et al., 2005)	3 VEs from the IREX system, which projects the participant's image onto a screen, where they interact with the VEs. VE 1 - soccer goalie task; VE 2 – stepping; VE 3 – Shark bait See http://www.gesturetekhealth.com/products-rehab-irex.php	Stroke, > 6 months post stroke	10 stroke patients, no recruitment info.	2 groups, no-treatment control, VR-training groups	BBT, FMA, MFT	5 60 minute sessions per week, for 4 weeks	Mann-Whitney U test compare pre-post test change, and group values	Control group showed no significant improvement. Treatment group showed significant improvement on all measures.	19
(Kuttuva, et al., 2006)	VE viewed on PC-monitor. Tracking sensor attached to patient's wrist was the interface device. VR task 1: grasp, lift, place VR objects. Task 2: volley a ball back and forth removing bricks at the back of the VE.	Left middle cerebral artery infarct, 17 months post stroke	1 stroke patient, no recruitment info.	None	FMA, wrist displacement, arm speed	4 weeks, 3 sessions per week	None, raw scores pre-post test provided	The participant improved on all variables	7
(Stewart, et	VE viewed on a PC-	Hemiparetic	2 stroke	None	FMA, BBT,	3 weeks, 4	None,	Both participants	12

al., 2007)	monitor, through 3D glasses. Tasks 1-3 used a magnetic tracker on participant's hand as the interface device. Task 4 used two haptic sensors, one on the forefinger and one on the thumb. Four VR tasks. Task 1: reach for cubes and 'hit' one cube at a time. Task 2: reach to intercept a ball shot from the wall in the VE. Task 3: reach to touch targets in the VE. Task 4: pick up and move cubes with thumb and forefinger.	stroke, >1month post stroke	patients, no recruitment info.		FTHUE, SIS	1-2 hour sessions per week	percentage change pre-post test provided	improved in FMA, BBT, FTHUE, SIS. Only one participant improved BBT score	
(Yeh, et al., 2007)	Same system as Stewart et al., 2007	Severity not described	5 stroke patients, recruited from University of Southern California	None	Movement efficiency, movement speed and task performance time	12 2 hour sessions	None, pre-post test results presented graphically for one participant	All participants improved across all variables. However, supporting data for only one participant provided.	9

Teacher-animation system results. Thirteen programs were based on teacher-animations (see Table 2.4 for references). These systems all incorporated an animation into their VEs to guide participants' movement during task performance. These animations may be a complete arm (for example (Gaggioli, et al., 2006)) or simply a cursor viewed in the VE (e.g. (Piron, et al., 2007)). Of the teacher-animation articles 10 were from two research groups—Holden and Piron. Holden et. al based their design on the theory that people plan arm movements based on end-point trajectory. Thus, their system used teacher-animations to demonstrate the endpoint trajectory of movements during task performance, assisting participants to better plan their actions. The Holden studies used a virtual teacher to demonstrate endpoint trajectory while mailing a letter, or pouring water in the VE. Piron et al. argued that teacher-animations provide AF, helping to guide movement patterns, and focus participants' attention on improving specific aspects of movement, for example accuracy. Accordingly, in these studies participants used real objects (such as an envelope) equipped with a magnetic tracking receiver to move a cursor seen in the VE through a series of targets set by the therapist. Other programs were not goal directed. These required participants to mimic the actions of the teacher-animation in virtual space. For instance, participants in Gagglioli et al.'s (2006; 2007) research performed a reaching movement with their less-effected arm, which was recorded by the system then inverted and replayed on a horizontal display to provide the teacher-animation for their more-impaired arm. Participants would then replicate the movement with their impaired arm over the animation. The program measured discrepancies between the animation and movement with their impaired hand.

The majority of these studies (8) were conducted using small-*n* designs. The mean DB score for these articles was 15.2, indicating moderate support. The study details and DB scores are presented in Table 3.4.

Table 3.4.

Details for studies aiming to improve upper-limb function using teacher-animation based VR systems.

Article	Description of VR system: Interface device & workspace	Severity of ABI, and any clinical measures*	Recruitment procedures	Control groups used	Outcome variables *	Duration of intervention	Statistical analyses	Results of intervention	DB score
(Gaggioli, et al., 2006)	VE displayed on a horizontal screen. Tracking sensors on the hand used as the interface device. Task: match arm movement of their more disabled arm to the recording of the same movement made with their better-recovered arm.	Right hemisphere stroke 13 months post stroke	1 stroke participant, no recruitment info.	None	FMA, ARAT	4 weeks, 3 sessions per week	None, percentage change on outcome measures provided	Participant improved both FMA and ARAT scores post test.	9
(Gaggioli, et al., 2007)	Same system as Gaggioli et al., 2006	Stroke, 1-6 years post stroke, all experienced hemiplegia	9 stroke patients, recruited from local rehabilitation facility	None	FMA, ARAT	8 weeks, 3 sessions per week	*t*-tests on pre-post test data.	No significant improvement	18
(M. Holden, Todorov, Callahan, & Bizzi, 1999)	VE displayed on PC-monitor. A real letter with attached tracking marker was the interface	Cerebrovascular accident, 1-4 years post stroke. FMA scores pre-treatment.	2 stroke patients, no recruitment info.	None	FMA, SAILS	16 1-2 hour sessions	None, numeric and percentage variation provided	Minor improvement on both measures	10

	device. Task: to copy the actions of a VR animation demonstrating a movement to post a letter.								
(M. Holden, Dettwiler, et al., 2001)	VE displayed on PC-monitor. A real water jug with a sensor attached was the interface device. Task: to copy the actions of a VR animation demonstrating how to pour water from a jug.	Acquired brain injury, 3-18 years post incident. FMA scores pre-treatment.	4 Acquired brain injury patients, no recruitment info.	None	FMA, ETUEF	32 sessions	None, pre-post test percentage improvement provided	Minor improvement in both measures	9
(M. Holden, Dyar, Callahan, Schwamm, & Bizzi, 2001)	Tested the systems used in Holden et al., 1999 and Holden et al., 2001	Stroke, 6 months – 4 years post stroke. FMA scores pre-treatment	7 stroke patients, no recruitment info.	None	FMA, WMT	10 weeks, 3 1 hour sessions per week	None, pre-post test percentage change provided	All participants improved pre-post test on both measures	14
(M. Holden & Dyar, 2002)	VE displayed on a PC-monitor. A tracking sensor on participant's hand was the interface device. Task: to copy basic movement patterns (e.g. reaching) made by the virtual	Stroke, several years post stroke. FMA scores pre-treatment	9 stroke patients, no recruitment info.	None	FMA, WMT	10 weeks, 3 1 hour sessions per week	*t*-tests performed on pre-post test data	Significant improvement on FMA. Significant improvement on 2 sub-scales of WMT	19

	teacher-animation.								
(M. Holden, Platz, Dyar, & Dayan-Cimadoro, 2007)	Same system as Holden & Dyar, 2002	Stroke > 6 months post stroke	11 stroke patients, no recruitment info.	None	FMA, WMT	10 weeks, 3 1 hour sessions per week	ANOVA tests performed on pre-post test data	Significant improvement for all participants on both measures	20
(Montagner, et al., 2007)	VEs displayed on a large projector screen. Force feedback exoskeleton used as interface device. 3 VR tasks. Task 1: Reach to touch buttons seen in the VE. Task 2: trace circle targets displayed in the VE. Task 3: Rearrange cubes in the VE to make a picture.	Stroke, > 1 year post stroke	3 stroke patients, no recruitment info.	None	Movement smoothness (measured by the system)	6 weeks, 3 1 hour sessions per week	None, graphical and numeric changes provided	Improvement in movement smoothness pre-post test	9
(Piron, et al., 2003)	VE displayed on a flat wall screen. Real objects with tracking sensors were the interface devices. Task: to move real objects (envelope, hammer, drinking glass) to match a	Stroke, > 3 months post stroke	24 stroke patients, no recruitment info	Conventional therapy, VR therapy groups	FMA, FIM	5-7 weeks, 5 1 hour sessions per week	Wilcoxon tests used to assesses within group change, Mann-Whitney U tests assessed between groups change	Both groups improved significant pre-post test. No significant between groups change	15

	virtual arm movement.								
(Piron, et al., 2004)	Same system as Piron et al., 2003	Ischemic stroke, > 1 year post stroke	5 stroke patients, no recruitment info.	None	FMA, FIM	4 weeks, 5 1 hour sessions per week	Wilcoxon tests used to assesses within group change	Significant improvement in FMA score, no significant change in FIM scores	13
(Piron, et al., 2005)	Same system as Piron et al., 2003. However, an extra task (putting a ball in a basket) was included.	Ischemic stroke, > 6 months post stroke. FMA scores pre-treatment	50 stroke patients, recruited from their rehabilitation. facility.	None	FMA, FIM	4 weeks, 5 sessions per week	Wilcoxon tests, Mann-Whitney U test, Spearman's Rho correlations	Participants demonstrated significant improvement between pre-post test	23
(Piron, et al., 2007)	Same system as Piron et al., 2003	Stroke, < 3 months post stroke	38 stroke patients, no recruitment info.	VR therapy, and conventional therapy groups	FMA, FIM	5-7 weeks, 5 1 hour sessions per week	Wilcoxon tests used to assesses within group change, Mann-Whitney U tests used to assess between groups change	Both groups improved significantly pre-post test. No significant between groups differences.	18
(Turolla, et al., 2007)	Same system as Piron et al., 2005	Stroke, > 6 months post stroke	30 stroke patients, recruited from their rehabilitation. facility	VR therapy, and conventional therapy groups	FMA, FIM	4 weeks, 5 1 hour sessions per week	Wilcoxon tests used to assesses within group change, Mann-Whitney U tests used to assess between groups	Both groups improved significantly pre-post test. VR group improved	22

change.	significantly more on FMA, but not on FIM scores.

Abbreviations of measures
ARAT – Action Research Arm Test
BBT-- Box and Block Test
CMSA -- Chedoke McMaster Stroke Assessment
ETUEF-- Emory Test of Upper Extremity Function
FIM – Functional Independence Measure
FMA – Fugl-Meyer Assessment of Motor Function
FTHUE -- Functional Test of the Hemiparetic Upper Extremity
JTAF – Jebsen Test of Arm Function
MFT – Manual Function Test
PPT – Purdue Pegboard Test
RLA -- Rancho Los Amigos Functional Test of the Hemiparetic Upper Extremity
SAILS -- Structured Assessment of Independent Living Skills
SIS – Stroke Impact Scale
WMT – Wolf Motor Test of Upper Extremity Function

Summary

Overall, the broad aim to improve general arm function among stroke and TBI populations was moderately supported by the complement of studies. Although both game-like and teacher-animation systems received moderate support, the latter scored higher. However, an independent samples t-test (conducted based on equal variances following a Levene test, $p = .45$) demonstrated no significant difference in DB score between the two groups, $t(17) = 0.91$, $p = .38$, $d = .40$, 95% CI (-0.51, 1.31).

Discussion

The findings of this review indicate that research on the effectiveness of VR upper-limb rehabilitation is still exploratory. Despite innovations in the design of the VR systems, research has been largely conducted using uncontrolled, small sample designs. Furthermore, studies were almost exclusively conducted among stroke patients. This highlights a pressing need to include TBI populations in research in order to support the application of VR. Based on the DB scale results, there is moderate support for this technology. On this basis, more rigorous studies are warranted to further investigate the effectiveness of VR. For example, timelines and intensity of effective interventions, and which patients are likely to benefit most from VR-training. Such studies will ensure that this technology can be implemented with confidence in clinical settings. Of the studies reviewed, teacher-animation programs scored higher on the DB scale than game-like systems. However, this difference was not significant, and both groups still provide moderate support. It should also be noted that even though moderate support was attained, the average score for these studies was only two points above the cut-off between ‘moderate’ and ‘poor’. Indeed, many studies were classified as poor. In short, these facts emphasise the need for caution in implementing VR-rehabilitation prior to more substantive evidence.

Assessment of Overall Methodology

As seen in Table 3.2, there has been a general increase in the number of studies published over the last nine years. This increase is due in part to the advent of new academic conferences in neurorehabilitation and applications of VR (such as the *Virtual Rehabilitation*, http://www.aristea.com/iwvr2007). Indeed, many studies published in 2007 were from conference proceedings. Although there is little change in the mean DB scores over time, the number of papers scoring above average for this field has increased from three between 1999 and 2003, to seven studies between 2003 and 2008. This may indicate a general shift towards more sound research designs. However, when the control procedures and DB sub-scales are considered further, it is evident that some areas of conceptualisation and methodology, like external validity, require more improvement than others, such as use of established outcome measures.

Control Procedures

Although the limited number of larger-sample studies did employ control group(s), in some cases the choice of groups did not permit evaluation of treatment effects. For example, Fischer et al. (2007) divided participants into two treatment groups and one ‘control’. However, all groups received VR-training but with different levels of assistance in performing the reach-to-grasp activities. Thus, the efficacy of their VR compared to normal rehabilitation was unclear. Accordingly, better use of control groups among larger sample studies is required to isolate the impact of VR-rehabilitation.

The small-*n* studies also employed control methods that did not clearly demonstrate the efficacy of VR. Traditionally, single participant designs have been used to reasonable effect in TBI and stroke research, permitting comparisons between treatment conditions over time (Jackson, 2006). Variations on the standard AB time-sequence design have featured previously, where performance is measured during baseline phase(s) (A) and treatment phase(s) (B). Among those studies that did employ an AB method (Broeren, et al., 2004; M. Holden, Dyar, et al., 2001), only a single assessment was conducted per phase. This procedure does not permit a stable baseline to be established nor evaluation of the trajectory of change. This makes it difficult to attribute improvements in function to the treatment, rather than random variations in the test environment or within the individual.

Reporting Sub-scale

Generally the complement of studies rated highly on the reporting sub-scale, compared to the others (see Table 3.1). In particular, study aims were clearly stated and characteristics of the sample and treatment populations were adequately described. However, poor identification of confounding variables, reporting of possible adverse events, and description of whether participants were lost to follow-up were common limitations.

Several methodological changes could be made in the future to account for confounding variables and adverse effects. Potential confounding variables include whether participants are undergoing concurrent rehabilitation, and their previous experience with VR technology. Furthermore, research has documented cases of illness similar to motion sickness (termed 'cyber-sickness') following use of VR technology (M. Holden & Dyar, 2002). Although several studies did state that no participants experienced cyber-sickness, all researchers should report on this as a matter of course. The representativeness of samples can also be better determined by reporting on the number of participants who were removed or dropped out of the study, and the reasons why. Finally, those studies that included statistical analyses generally did not report exact probability estimates. Reporting exact probabilities (and effect sizes, where appropriate) will help temper the interpretation of significance tests, enable a more balanced discussion of results, and allow accurate inter-study comparison.

External Validity Sub-scale

This sub-scale is based on details about recruitment procedures and the setting where the evaluation was conducted. The studies scored very poorly on this sub-scale. Many papers scored zero for all three items, and none received a full score. Thus, the external validity of this research can be considered a major limitation to date.

Although not directly assessed by the DB scale, clinical significance data that reflects functional improvement is crucial in establishing external validity. Clinical significance is the theory that an intervention may not produce statistically significant results, yet improve patients' lives (the opposite may also occur) (Ogles, Lunnen, & Bonesteel, 2001). The studies reviewed here did not report quantitative clinical significance data. Further, qualitative clinical significance information was only provided by three studies (M. Holden, et al., 1999; Jack, et al., 2001; Sveistrup, et al., 2003). Of these, one noted improvements in fine-motor skill (Jack, et al., 2001), and two in gross-motor (M. Holden, et al., 1999; Sveistrup, et al., 2003). Accordingly, future research could include more evidence that VR-therapy has a real world impact on patients' lives through systematic clinical significance analysis (see (Campbell, 2005) for discussion), and assessments of functional change.

Bias Sub-scale

The studies reviewed generally scored well on this sub-scale. However, there were some inconsistencies. Almost all scored highly for conducting only preplanned analyses, having consistent treatment administration, treatment adherence, and utilising sound outcome measures. Further, studies that did employ statistical procedures used tests appropriate to their aims, such as *t*-tests, and ANOVA. Despite the fact that blinding participants to group may be difficult with VR technology (i.e., creating placebo systems may be impractical), blinding the administrators of treatment and assessment protocols may be possible in future studies.

Internal Validity/Confounding Sub-scale

This sub-scale assesses whether any bias is present in the selection and distribution of participants for the study. The studies reviewed did not score highly on this sub-scale. Few researchers indicated the timeline for recruitment (over how many months, and during which years), and whether they were from the same cohort (i.e., whether participants were recruited from multiple sites). As well, none attempted to conceal the allocation of participants to groups. Finally, confounding variables and drop-out rates were not well reported, creating potential sources of error.

Power Sub-scale

This sub-scale rates whether the negative findings from a study could be due to chance, based on sample size. The studies scored moderately well on this sub-scale. Further, while this finding indicates that (according to the DB criteria) adequate sample sizes were used, many studies still had samples which would be considered low power (Howell, 2002). Based on the DB scale a study with 10 participants would score the same as a study with 100 participants (a much higher power sample). Thus, the DB scale may give an inflated representation of statistical power. Nevertheless, by statistical standards, existing research can still be considered low power.

Limitations to Review

There are aspects of the present review that could be improved. Firstly, database searches were limited to English language studies. Peer-reviewed research published in other languages could be included in future reviews. Secondly, some items on the DB scale, such as whether participants were blind to group allocation, may be difficult to achieve with VR technology. Thus, receiving a full score on the DB scale may be unreasonable for this research.

Summary of Chapter 3

One of the current limitations to VR-rehabilitation is whether sufficient evidence exists demonstrating its benefits. The systematic review presented in Chapter 3 indicated that there is only moderate support for VR-rehabilitation based on the DB rating scale. This outcome means that the current data should be considered preliminary, yet it provides sufficient justification for further development and trials of VR-systems.

This review identified 23 studies that investigated the clinical benefits of upper-limb VR-rehabilitation among TBI and stroke patients. Twenty-two of these were conducted on stroke patients. This shows that, despite the potential advantages to TBI rehabilitation offered by VR, this population has been neglected in intervention research. Ten of these studies trialled (video) game-like systems. These programs provided fun VEs that encouraged participants to achieve a specific goal for the game (e.g. using a mouse to bounce a ball against a wall of bricks to reveal a picture (Kuttuva, et al., 2006)). Four of these studies were conducted by the Rutgers group. Their program aimed to improve participants' hand strength, speed, range of motion, and finger fractionation (see Table 3.3 for details). Based on the DB scale, only moderate support was evident for game-like systems.

The other group of VR-programs utilised teacher-animations in their design. These programs provide participants with an animation (e.g. an entire arm) that demonstrates a movement, which participants replicate. Participants are informed on the similarity between their movement and the animation's. Ten of these studies were conducted by the Holden and Piron groups. Both of these systems required participants to move real objects with tracking sensors to match the animation's action (e.g. mailing a letter). Congruent to the game-like systems, only moderate support was evident for the 13 teacher-animation studies.

This review identified several areas for improvement in future studies. These included increasing internal and external validity, use of appropriate control procedures, and larger-sample investigations. In trialling the Elements system we aimed to overcome these limitations by utilising appropriate control procedures, and statistical analyses. These studies are described in Chapters 5 and 6.

In addition to evaluating the empirical evidence supporting VR-rehabilitation, this review aimed to describe previous VR-programs (see Tables 3.3 and 3.4) to inform Elements' development. Accordingly, we formed four aims in designing our system. Firstly, the VEs would be engaging and fun for participants, to enhance their motivation for training. This is a central advantage to VR-rehabilitation generally (M. Holden, 2005; Rizzo, et al., 2004) and was an effective approach in other systems (e.g. (Adamovich, et al., 2004; Jang, et al., 2005). Secondly, Elements would be flexible in its design, allowing customisability of the training to meet patients' individual needs. Such customisability is a staple of TBI rehabilitation (B. Wilson, 1998) and other VR-training (e.g. (Gaggioli, et al., 2007)). Thirdly, we would employ established motor control theory in our system's design. Indeed, the theories underlying many of the VR-systems in this review were unclear (e.g. (Broeren, et al., 2004; Fischer, et al., 2007; Stewart, et al., 2007)). Finally, the Elements system would also serve as an assessment tool, automatically tracking key aspects of upper-limb function during task performance. Chapter 4 describes the Elements system’s development, and administration procedure.

CHAPTER 4

DEVELOPMENT OF THE ELEMENTS SYSTEM AND TREATMENT PROTOCOL

CHAPTER 4: DEVELOPMENT OF THE ELEMENTS SYSTEM AND TREATMENT PROTOCOL

Overview of Chapter 4

Chapter 4 details the Elements system, and administration protocol. It begins by presenting the theoretical basis for the program, including the ITE model, and the person-centered approach. The system components and administration protocol are then described, including the training schedule, the VEs, assessment functions, AF, and goal setting. The aim of this chapter is to provide a detailed description of the Elements VR-system, background on our design choices, and the administration process used during the empirical trials.

Theoretical Basis for System-design

From the perspective of the ITE model of motor behaviour (Shumway-Cook & Woollacott, 2007) TBI results in significant impairment at the individual level. Perception, cognition, and action systems can all be disrupted by trauma. In the context of altered individual constraints, the ITE model indicates that to retrain functional movement, rehabilitation should consider environmental and task factors (Law, 1996; Strong, et al., 1999). For instance, the difficulty of tasks must match participants' capabilities otherwise boredom, frustration, and reduced motivation may result. Additionally, teaching participants to distinguish environmental features that enhance or hinder performance is an essential part of rehabilitation (Law, 1996; McColl, et al., 2003; Newell & Jordan, 2008).

One of the main advantages of VR-rehabilitation is the high level of control it permits over therapeutic tasks and environments (Rizzo, et al., 2004). Therefore, under the ITE model, VR is an excellent medium for retraining movement post-TBI, since both task and environment factors can be tailored to the participant's needs, and leveraged to promote changes (or recovery) at a cognitive and functional level. In developing the Elements system, we applied a hybrid model of performance that blended the ITE model with insights from cognitive neuroscience (Wilson, et al., 2006). Here, motor behaviour was described at three levels: (i) neurocognitive bases of performance (i.e. the development and use of internal models for action which support adaptive, on-line movement), (ii) movement forms and patterns that describe participants' movement 'signature' at a given stage of recovery (i.e., assessment of kinetic and kinematic markers of movement proficiency), (iii) functional outcomes of the movement (Wilson, et al., 2006). Figure 4.1 illustrates this model.

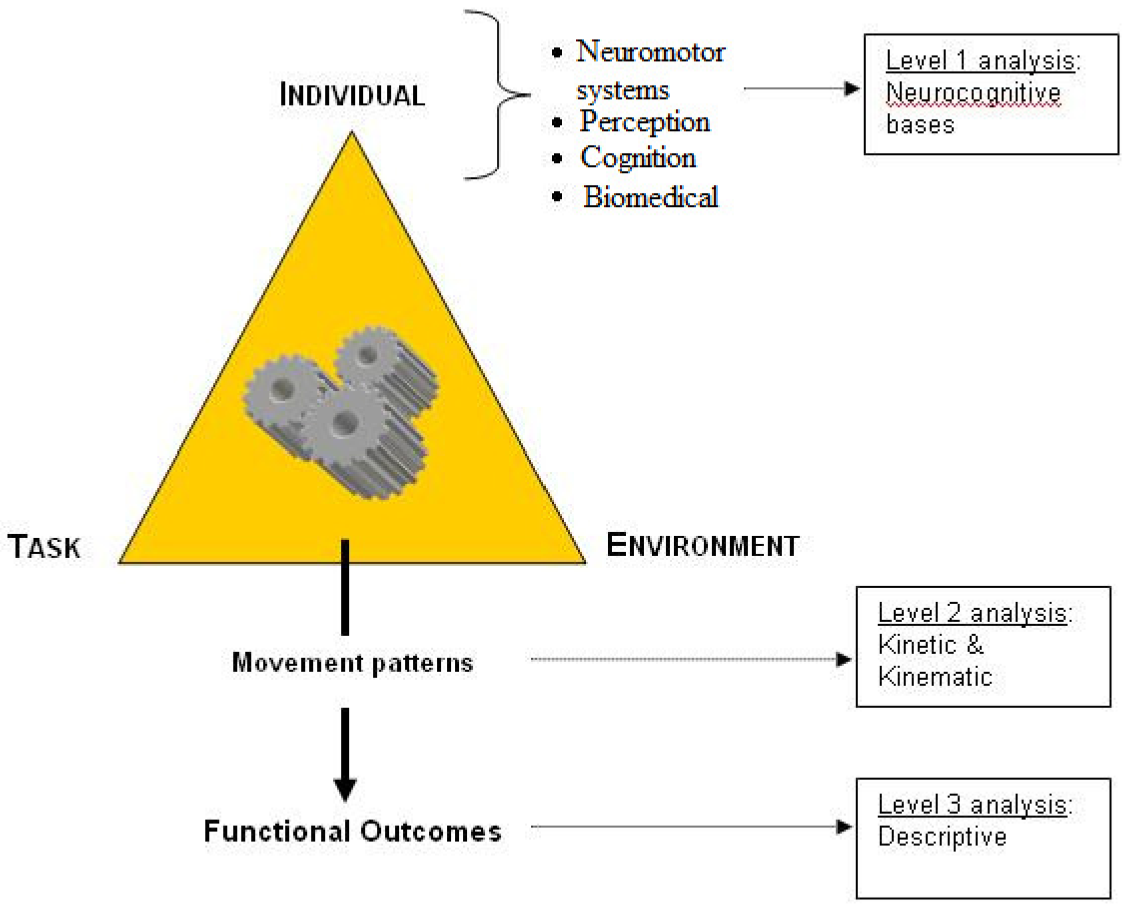


Figure 4.1. Diagram of the ITE model used in development of the Elements system.

Level 1– Neurocognitive Bases of Action

One crucial aspect of developing motor control post TBI is retraining the ability to use predictive control (or internal models of movement) (Bate, 1997). This may include either forward models (using a copy of the motor command to predict the future state of the moving limb and guide action) or inverse models (using knowledge of spatial layout to derive the necessary motor coordinates to achieve an action goal) (Flash & Sejnowski, 2001). Forward models contribute to volitional control by anticipating and cancelling out the sensory consequences of a given movement, enabling the observer to distinguish between self-produced and external effects (Shumway-Cook & Woollacott, 2007). Furthermore, providing participants with AF (detailed subsequently) promotes multimodal integration, allowing users to recalibrate the relationship between their movement and its sensory consequences. Provision of AF facilitates development of predictive control of movement, and forward modelling (Bate, 1997).

Level 2– Movement Form and Strategy

Movement form and efficiency reflect the particular movement solutions adopted by the recovering patient, which may or may not realize the intended functional goal. Indeed, successful completion of functional tasks may be impossible or laboured during the early stages of recovery. Assessment of kinematic and kinetic parameters can help the clinician describe which aspects of coordination, timing, synergy, or force production may not be adaptive (Wilson, et al., 2006) . The Elements program was designed to automatically track three basic movement parameters (accuracy, speed, efficiency, which are discussed below). Performance on these variables was monitored throughout training to provide data on movement abilities, and inform treatment.

Level 3 – Functional Performance

In TBI rehabilitation therapeutic tasks need to hold clear significance for the participant, and ideally the action needs to be purposive, since it is at the level of goal representation that motor intention is mapped to the trajectory of limb movement (Wilson, et al., 2006). Furthermore, in VR- rehabilitation the VEs need to promote meaningful action. Thus, the Elements program required participants to interact with and move a tangible use interface (TUI), with each VE encouraging an appropriate grasp, lift, place action. The VEs were also designed to present movement tasks that were aesthetically pleasing, engaging and challenging for the participants.

Facilitating Improvement

Administration Approach

In administering the Elements training we adopted a person-centered approach, which emphasises the therapist's attitudes and their relationship with the patient as key to promoting recovery (see (Elliotta & Freire, 2007; Raskin, 2004) for review). This approach has been used successfully with TBI patients previously as part of their psychological therapy, particularly in treating depression (e.g. (Cicerone, Fraser, & Clemmons, 2000; Schneck, 2002)). Indeed, motor control research (among children with developmental coordination disorder) has demonstrated that the style and attitude of the therapist may be as important in motor-learning as task content (Sims, Henderson, Morton, & Hulme, 1996). Therefore, during the Elements training maintaining a friendly relationship/rapport with the participants was important for keeping the atmosphere positive and enjoyable.

Additional Factors

Several additional factors were thought to influence participants' improvement while using the Elements system (based on the ITE model), and were considered during administration.

Individual factors. Participants needed to be mentally ready for the session, and to improve their function. At the start of each session, we conducted a 'readying' period, to prepare the participant and focus them on the task at hand. This type of mental preparation has been successfully used in sports training (Robazza & Bortoli, 1998) and was achieved using simple statements:

- Asking participants to 'switch on', when it was time to perform the tasks
- Asking them to say if they were 'ready' before commencing the task
- Getting them to 'leave behind' anything unrelated to the training (i.e. to not focus on other distracting events that may have occurred during their day), and promoting the idea that all that matters now is performing these tasks.

Participants' were encouraged to use effective movement patterns, and instructions were given to help with any difficulties. The two most common were:

- Sliding the object rather than lifting: 'let's try that task again, this time I want you to lift the object up as much as you can, then place it on the targets'
- Not seeing targets and missing them: 'remember to scan your environment for the next target as you go'.

Task factors. The main task related factor was to ensure participants understood the VEs. For example, only move the object to the targets in Go No-Go (discussed below). Also, to avoid presenting tasks that were too challenging. Attempting tasks beyond their capabilities may be frustrating for participants, and reduce motivation (Siegert & Taylor, 2004).

Environmental factors. Distractions in the environment were minimised, for example, unrelated noise. Participants were also comfortably seated to perform the tasks. They were also helped to understand the AF features if needed.

Summary

To summarize, the primary aims in creating the Elements system were to produce a therapeutic tool that would capture users' attention, and afford natural interaction, while enhancing their knowledge of the relationship between sensory-perceptual consequences. Further, the system would be tailored to participants' individual needs. The VEs were to be compelling and highlight the natural affordances offered by objects to maintain the ecological validity of the training, and maximize movement development. In short, we aimed to design rehabilitation and assessment activities that utilize real objects, provide movement feedback, and challenge participants' motor planning.

The Elements System

Overview

The Elements system has both assessment and rehabilitation functions. For assessment the system automatically tracks participants' movement accuracy, speed, and efficiency. This data is output in Excel compatible files for analysis. For rehabilitation Elements aims to improve participants' upper-limb function and consists of two forms of interaction, goal-based and exploratory. The four goal-based tasks share a stimulus-response format, and progressively challenge participants' motor planning. These tasks require them to move a TUI to cued locations on a horizontal LCD display. During the tasks participants receive visual and audio AF to assist them in redeveloping predictive control of their movement. The three exploratory VEs do not cue participants' movements. These tasks encourage user-directed movements, and utilise multiple TUIs. The Elements training consisted of 12 one-hour sessions over 4 weeks. Figure 4.2 presents a schematic diagram of the Elements system, outlining its assessment and rehabilitation functions.

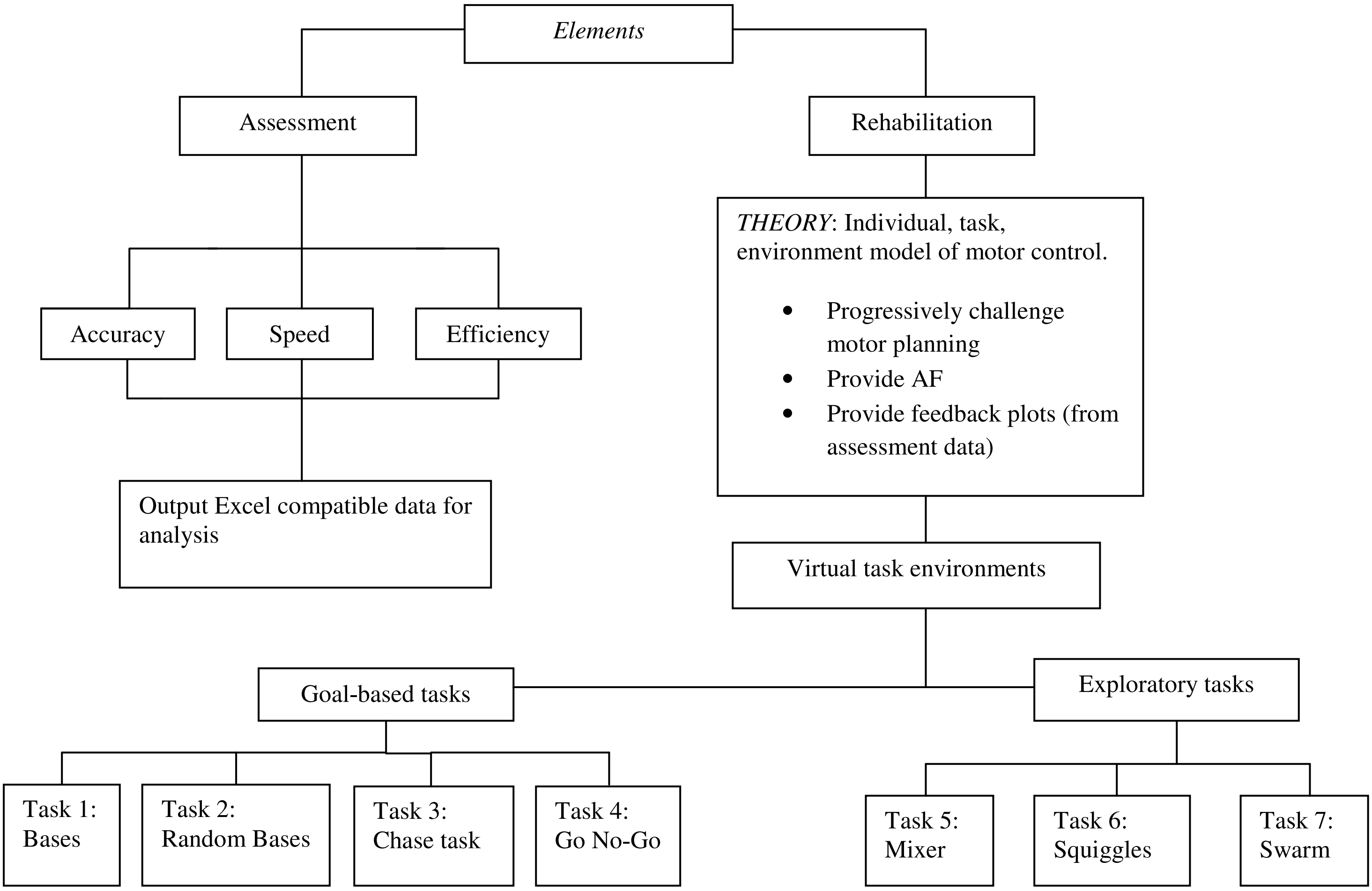


Figure 4.2. Schematic diagram of the Elements system showing the assessment and rehabilitation functions.

Hardware

PC Components

The Elements system runs on commercially available computer hardware. The PC used in our trials contained an AMD Athlon64 X2 Dual Core 4400+ (2.21GHz) processor, 2GB RAM and an nVidia GeForce 7800 graphics card. The VEs were displayed on a 1020 mm (42 in.) LCD panel, with audio cues presented via stereo speakers. The panel was covered by a piece of non-reflective hardened glass (see Figure 4.3a for the system set up).

TUIs

The program uses four TUIs (objects), which participants move on the display to interact with the VEs. The task environments were designed to engage participants' attention and afford immediate possibilities for action. Thus, rather than embedding the objects in a virtual world, the system used real objects to promote direct interaction. The four objects are basic forms, each with a different shape and colour (see Figure 4.3b). The triangle, rectangle, and hexagon were made of silicon rubber and a felt covering, each weighing approximately 350g. The circle object was made of ABS plastic and felt weighing approximately 250g. These shapes and sizes were designed to be engaging, and maximise the grasp, lift, place affordances in the VEs (see (Duckworth & Wilson, in press) for further discussion on the use of TUIs in VR, and in the Elements system)

Tracking System

Movement of the objects is tracked using the Bumblebee 2a camera system from PointGrey (seen in Figure 4.3a), which has pre-calibrated stereo cameras for accurate depth measurement. The accuracy of the tracking system is within 0.1mm.

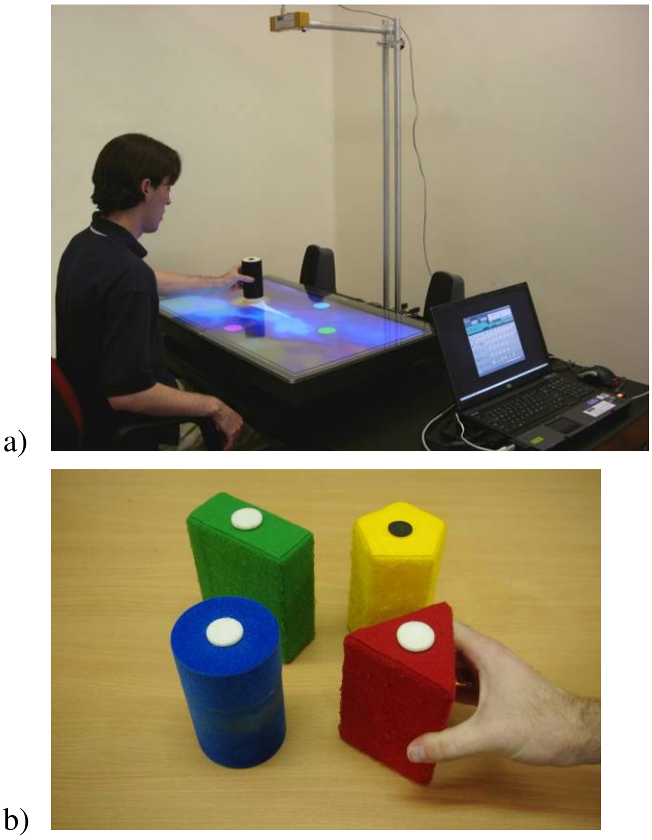


Figure 4.3. Photographs of the Elements system. a) System setup; and b) TUIs.

Software

Component software can be divided into four parts: visual tracking system, layout of the VEs, the operator interface (OI), and the database. Each will be outlined below. However, other collaborators on the Elements project were responsible for programming the system, and their respective publications should be consulted for further details (Duckworth & Wilson, in press; Duckworth, et al., 2008; Eldridge & Rudolph, 2008; Eldridge, et al., 2007).

The stereo-tracking system was initially developed using Compass 3D, then finalised using Open CV. The tracking system identifies, and tracks, a round marker on a contrasting background on top of each object (as seen on each of the objects in Figure 4.3b). The system distinguishes each object by the hue and saturation of its colour (blue, yellow, green, red).

The graphic layout, soundscape, and interaction design of the VEs were developed using the Virtools Dev 4.0 authoring program. Virtools allows the creation and coordination of ‘building blocks’ which perform the operations comprising the program. For example, in Elements, one building block was responsible for receiving and analysing the camera’s data, another for producing the sound feedback, and so on (readers are referred to the Virtools home site www.virtools.com for further discussion on the features of this program).

The WxWidgets program was used for creating the OI, and running the Virtools based VEs (see Figure 4.4 for the layout of the OI). The OI lets the clinician start each of the Elements tasks, and vary aspects of each. For example, the number of cycles for a task, and which AF is used. Additionally, the OI allows participant data to be extracted and output to Excel for analysis. The OI was designed to be easy to use, and intuitive. The database was developed using MySQL, and was responsible for storing, and retrieving participants’ data.

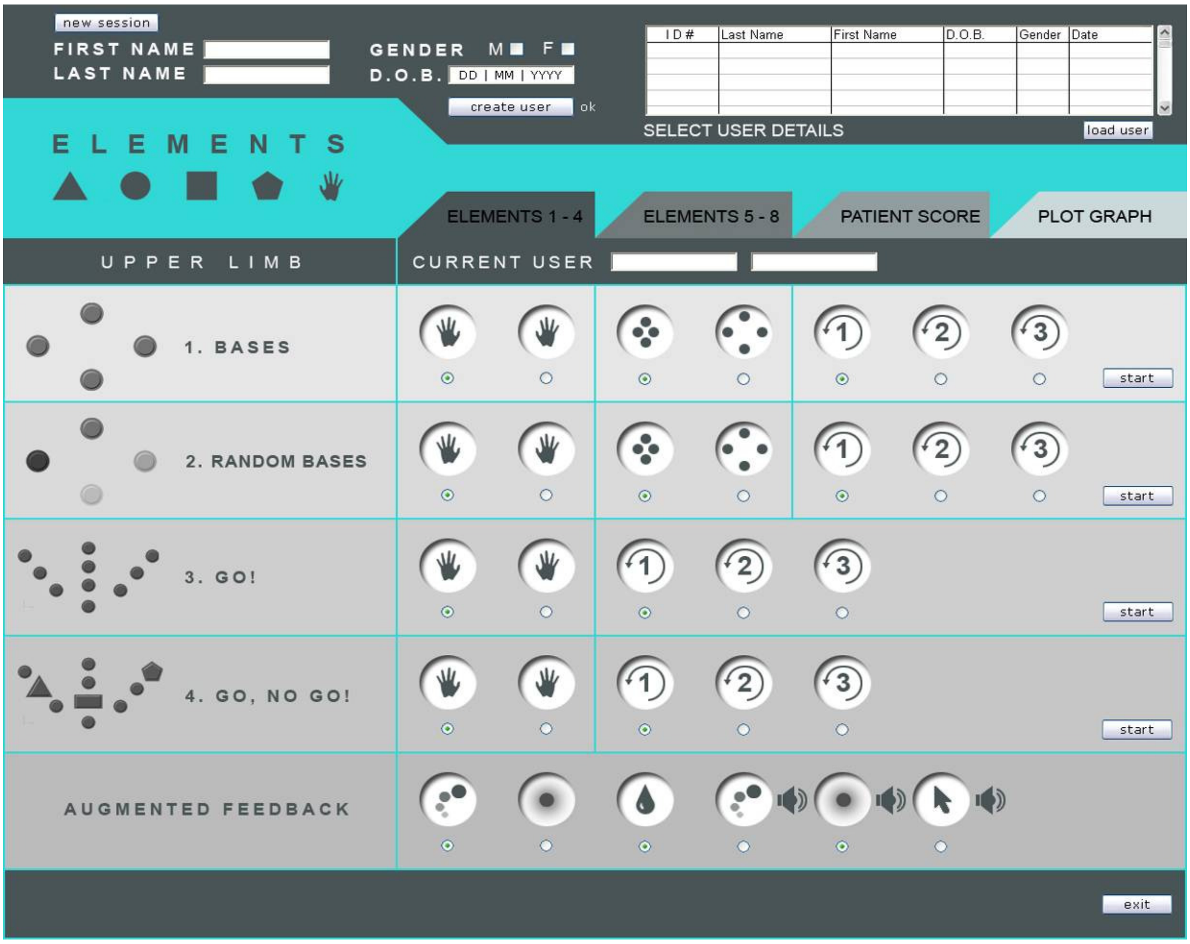


Figure 4.4. Screenshot of the OI.

Administration Protocol

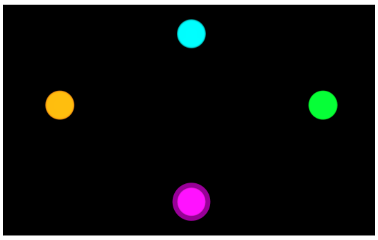
Virtual Environments

The movement prototype used in the Elements training was a basic grasp, lift, and place action. The tasks were designed to place progressively greater requirements on participant's motor planning and forward modelling (Flash & Sejnowski, 2001). Thus, based on the ITE model, we wanted the goal of the tasks to remain clear, while varying task difficulty and environmental constraints according to the participants' emerging capacity to organise and execute movement. Furthermore, the use of TUIs (rather than a purely virtual form of interaction) was intended to complement traditional rehabilitation, since most physical therapy and OT involves object manipulation tasks (Hopkins & Smith, 1993). Since deficits in comprehending proprioceptive feedback are common post TBI, the TUIs also allowed us to integrate natural proprioceptive feedback with AF to improve the training's generalisability (Liebermann, et al., 2006). Accordingly, providing concurrent AF would theoretically promote a greater awareness of movement outcomes. For example, during the goal-based VEs participants experienced natural proprioceptive feedback from moving the circle object, which was reinforced by the sound AF (discussed in detail below).

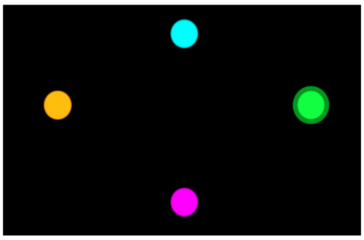
The goal-based VEs incorporate external cuing to trigger motor responses. Participants move the object to a designated location when prompted by the system. Hence, movement is initiated in response to external events which signal the required action. By comparison, the purpose of the exploratory VEs is determined by the participant. These tasks offered new movement environments (i.e. the three new VEs), yet involved the same basic actions used in the goal-based VEs, but specific movement is not cued by external events. Rather, the participant is required to discover by free movement the hidden structure in the environment and how they can manipulate the quality of different types of AF. Accordingly, we anticipated the exploratory VEs to compliment the rehabilitation process in three ways. Firstly, the self-directed nature of the exploratory VEs required participants to employ (and develop) greater intentional control of their movements than in the goal-based tasks. One of the issues with TBI is volition. These task environments were designed to allow patients to independently choose which movements to make, thereby promoting volition in their actions. Secondly, by using multiple objects the exploratory VEs encouraged greater bimanual action. Using a simple task format, it was thought that the exploratory bimanual activity would encourage the patient to explore their movement synergies under a reduced set of task constraints. It was hoped that this would provide a platform for more complex bimanual action in their other rehabilitation, and daily life. Previous research has suggested that including both bimanual and unimanual activities during training would promote greater generalization of learned skills (Waller, Liu, & Whitall, 2008). Finally, we believed these VEs would be the most enjoyable facet of the Elements training, and would encourage participants' motivation and commitment to the process and a means of exploring new synergies within and between limbs over a sustained period of time.

Goal-based VEs

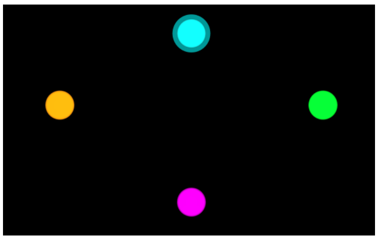
Task 1- Bases. To begin this task the circle object is placed at the bottom of the screen, approximately 25cm from the left or right edge (corresponding to the hand performing the task). This starting position is used for all goal-based VEs. Once the task is initiated the participants see four circular targets (approximately 6cm diameter), arranged in a north, south, east, west configuration. Each target is cued, in turn, by a flashing border (in an anticlockwise pattern, beginning with the south target), and the participant moves the object to each highlighted target (see Figure 4.5). Once the object is placed on the target (i.e. a score for accuracy has been registered) a ‘pulse’ effect is produced. Here the target increases to double its original circumference, then shrinks back to normal (this pulse occurs in all goal-based VEs). This VE has the simplest motor planning requirements, since the exact location, and order of the movements are known.



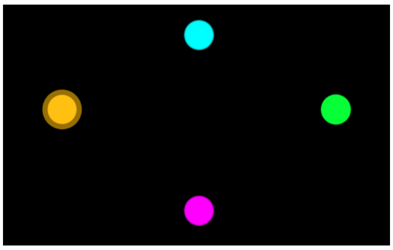
Home target highlighted



First target is highlighted.



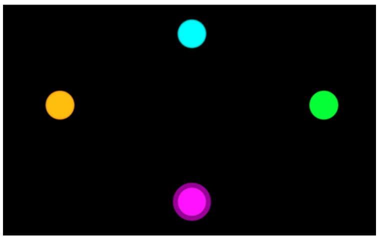
Second target is highlighted.



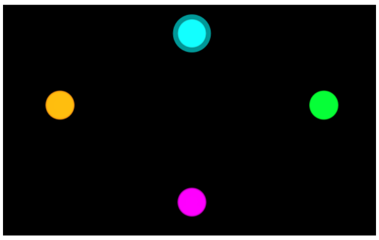
Third target is highlighted

Figure 4.5. Screenshots depicting the stimulus sequence for the Bases task.

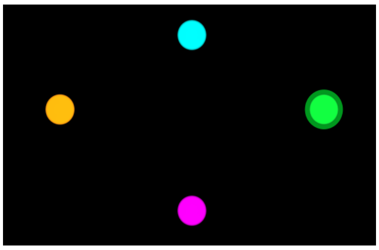
Task 2 – Random Bases. The configuration of target locations in this VE is like the Bases task. However, the targets are cued in random order, as shown in Figure 4.6. This task has a greater level of stimulus-response uncertainty than Bases, and places higher demands on participants' motor planning. They must plan to move the object to any of three known locations, but in an unknown order.



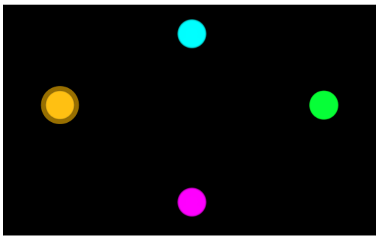
Pattern of target locations



First target is randomly chosen, and highlighted.



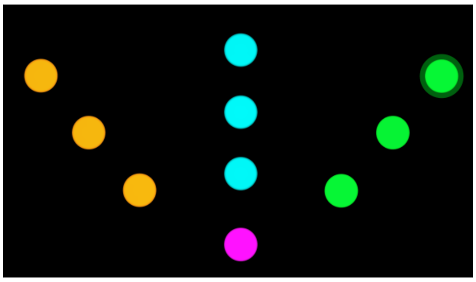
Second target is randomly highlighted.



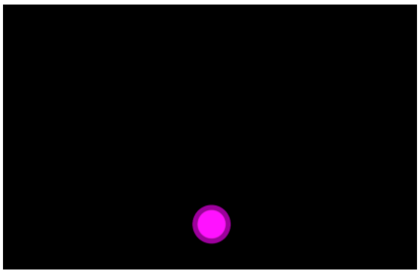
The remaining target is highlighted

Figure 4.6. Screenshots of a possible sequence of stimuli in the Random Bases task.

Task 3 – Chase task. This task has nine potential target locations, configured in a radial pattern (see Figure 4.7). The participant initially sees a blank screen, then one target randomly appears cuing movement of the object to that location. This target then vanishes (once the object is placed), another appears, and the object is moved to the new location. This process continues until all nine targets have appeared. In this task, targets are presented in a pseudo-random order. Hence, participants are unsure about the order and trajectory of each movement, until cued. This places greater requirements on participants' motor planning than the previous tasks, since both the location and order of movements are unknown.



Potential target locations.

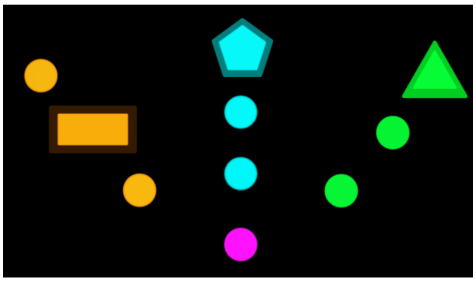


First target highlighted

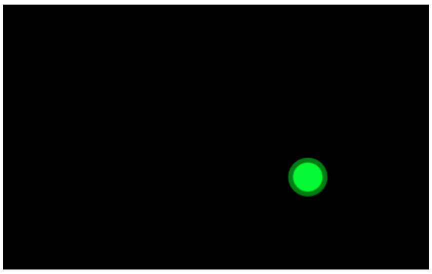
Next target is randomly selected.

Figure 4.7. Screenshots of the Chase task.

Task 4 - Go No-Go. This task is similar to the chase task. However, three distractor shapes (triangle, hexagon, or rectangle) are cued in addition to circular targets (Figure 4.8). Participants move the object only to circle targets, and no other shape. This task places the greatest demands on motor planning. Participants must simultaneously plan to move the object to an unknown location in the VE, and inhibit movement to the distractors (see (Jakobs, et al., 2009; Miller & Low, 2001; Rubia, et al., 2001) as examples of movement research using similar inhibition tasks).



Potential targets and distracters



Target is randomly selected

Distracter is randomly selected as next stimulus

Figure 4.8. Screenshots of the Go No-Go task.

Exploratory VEs

Participants were not informed about the exploratory VE's functions when introduced to them (contrasting the procedure with the goal-based VEs). Rather, they were asked to interact with the VE by moving the object(s) on the screen, and discover its functions. However, if participants were unable to understand an exploratory VE, verbal prompts were given, e.g. for the Mixer task 'see what happens when you place the object on one of the icons and slide it off without lifting it'. The exploratory VEs were more complex (both in terms of visual and auditory stimuli) than the goal-based tasks, which may have been distracting for participants. However, with a therapist present to ensure participants understood the task, and keep them focussed if they appeared distracted, we felt the risk to their progress was minimal.

Task 5- Mixer. The Mixer task uses only the circle object. This VE presents nine circular icons in a 3x3 pattern, each with a partial border around it (see Figure 4.9). The participant places the object on an icon to activate its sound, and start the border animation spinning. Participants can then slide the object over an icon to vary the pitch and tone of the sound. Or, they can place and slide the object off the icon to deactivate it. Accordingly, participants can activate combinations of icons, and vary their sound qualities, to produce an overall sound effect for the VE. Each version uses the same interaction method, but with different sound files for the icons.

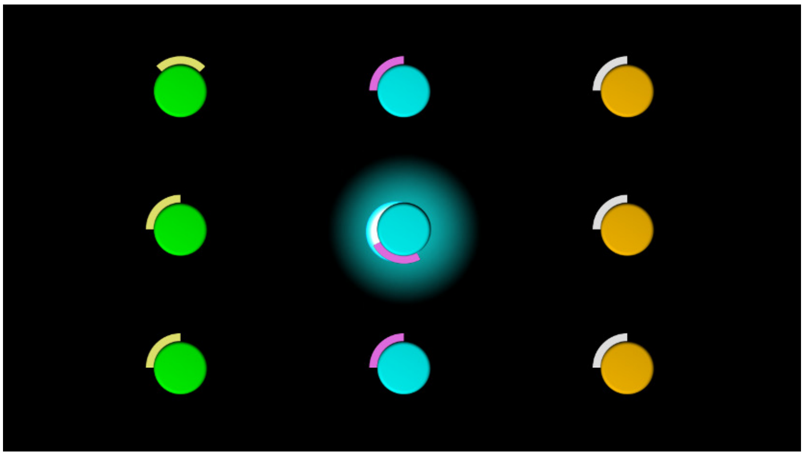
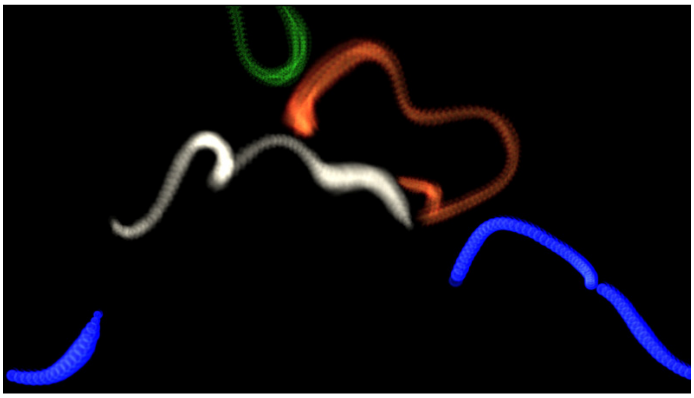
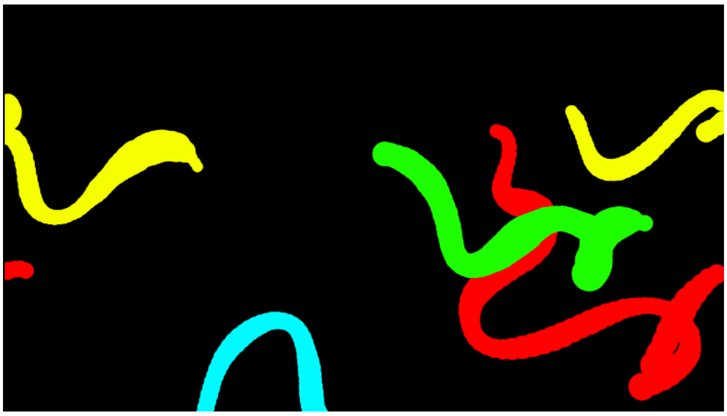


Figure 4.9. Screenshot of the Mixer task.

Task 6- Squiggles. This VE utilises all four objects. The participant is initially presented with a blank screen. Then, as each object is placed and moved across the screen a trail animation is drawn along its path, and a musical tone plays. Once the participant lifts the object the trail animates across the screen. Each object has a unique trail and sound. The three versions of this task have different trail animations, and sounds for the objects.



a)



b)

c)

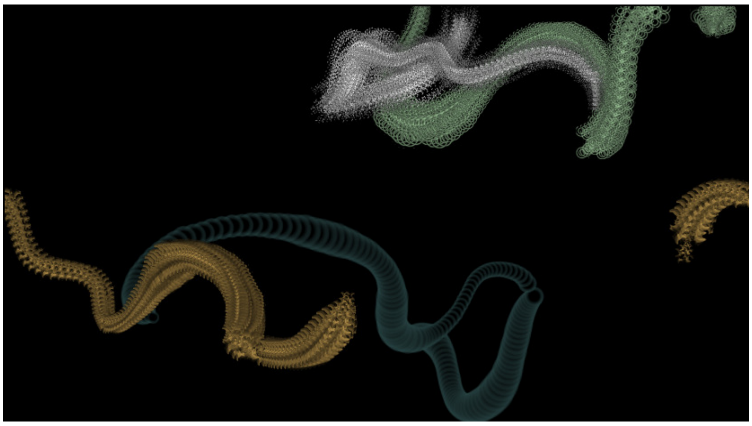


Figure 4.10. Screenshots of the Squiggles task. a) Version 1; b) Version 2; c) Version 3.

Task 7- Swarm. The Swarm task also uses all four objects. In this VE each object has a group of animated shapes that follow it across the screen (referred to as the object's 'swarm', see Figure 4.11). The swarm then clusters around the object once it stops. However, if the object remains stationary (for more than 5s) its swarm will disperse, and return again if the object is moved. The swarms also react to the position of the other objects. For instance, when the red and blue, or yellow and green objects are positioned together the swarms repel each other. The opposite combinations cause the swarms to cluster together. The VE also produces musical tones that vary with the objects' position. Thus, participants can move and position the objects on the screen to create swarm patterns, and sound combinations. The three versions of this task vary the size and shapes of the swarm animations, and the sounds produced. In version one the swarms are small triangles, circles, pentagons, or rectangles paired to their objects. In version two the shapes are consistent, but larger in size. Version three used stylised patterns matched to each object, such as fire for the red object. Figure 4.11 shows the three different swarm versions.

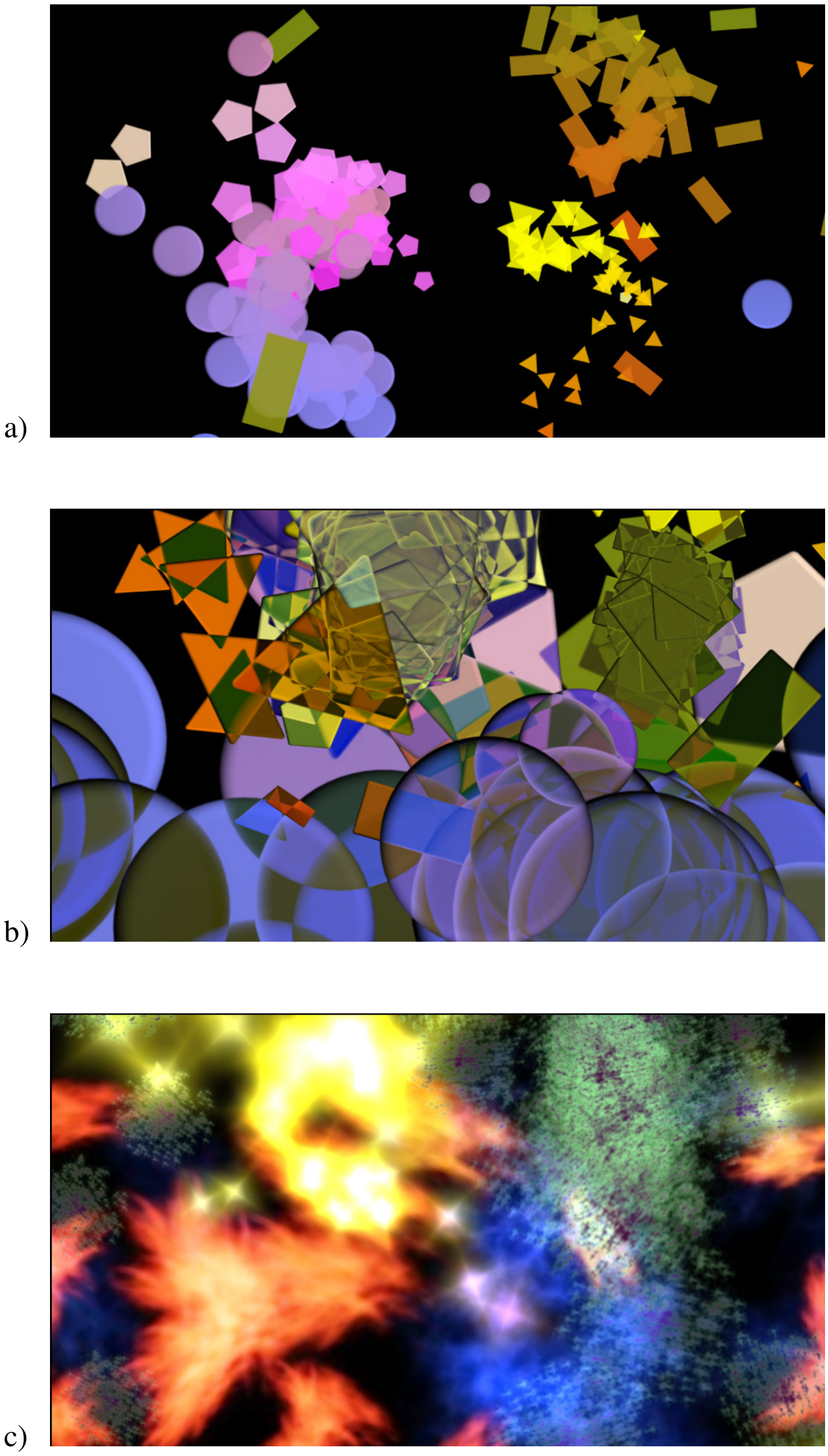


Figure 4.11. Screenshots of the Swarm task. a) Version 1; b) Version 2; c) Version 3.

Schedule for Training

The upper-limb training consisted of four weeks of therapy, with three sessions per week. Each session lasted approximately 60 minutes. The session length was based on recommendations by the American Occupational Therapy Association (AOTA) for treatment and assessment of TBI patients (Radomski, 2000). The treatment duration also mirrored earlier studies of VR- rehabilitation (e.g. (Broeren, et al., 2004; Kuttuva, et al., 2006; Piron, et al., 2005; Piron, et al., 2004)).

The program's administration is divided into four general phases, described in Table 4.1 below. This structure is in line with the three phase theory of motor learning (with an extra 'conclusion' phase), which states that motor-skill development passes through a series of stages that transition from slow, highly controlled movements, to rapid autonomous action (Hubert, et al., 2007). Under the ITE model this can be viewed as increasing coordination between the individual, and task/environmental factors over time. Recent evidence also supports this three-stage model of motor learning in TBI and the efficacy of rehabilitation founded on it (Mastos, Miller, Eliasson, & Imms, 2007).

Table 4.1

Treatment phases and theoretical basis for the Elements training.

Treatment Phase	Duration	Objectives	Theoretical model (Hubert, et al., 2007)
1. Introduction and familiarization with Elements	Sessions 1 & 2	To familiarize the participant with the Elements tasks, the AF, and goal setting. To allow adequate exploration of the virtual workspace.	This phase is congruent with the 'cognitive phase' of motor learning, where the performer must pay close attention, and consciously control all aspects of the movement.
2. Goal directed learning	Sessions 3 to 7	To complete goal setting, and begin achieving these goals (to improve movement speed, efficiency, and accuracy) by presenting the Elements tasks with AF. To present *variability* in the schedule of tasks with a view to long-term retention.	Phase 2 fits with the 'associative' period of motor learning where the learned movement is practiced extensively and becomes more automatic.
3. Consolidation/Automisation	Session 8 to 11	To meet performance goals, while maintaining the improved performance that has been established.	During the automisation phase of motor learning, the acquired skills are performed more automatically, with an increased degree of proficiency.
4. Conclusion and review	Final session	To review the participants' performance in terms of goal achievement, and conclude the therapy. To assess levels of movement control achieved as a result of treatment.	This phase is based on rehabilitation literature that recommends the final session of an intervention consist of a performance review (Radomski, 2000).

Task Presentation

The four goal-based VEs were presented an even number of times per session, and for both hands. Review of feedback plots (detailed below) followed. During Study 2 the last 5-10 minutes of the session participants interacted with one of the three exploratory VEs. Participants experienced the first versions of these in week one, the second versions in week two, and the third in week three. Then, during the fourth week participants selected the task and version for each session. In Study 1 the last 5-10 minutes were used for conducting assessments. Participants sat up straight while interacting with the VEs, without any physical positioning devices.

System-measured Variables

Three performance variables are recorded automatically by the system during the goal-based tasks. *Accuracy* of placement is measured as a percentage score and represents the overlap between the base of the object and the target. Thus, 100% would mean perfect overlap. *Movement speed* is given by the rate of object movement during the task in m/s. *Movement efficiency* assesses the deviation from the straight-line path between targets during movement, representing how smooth and controlled the movements were. This variable is measured as a percentage score: (total straight-line distance between the sequence of targets ÷ distance moved) x 100. Thus, a score of 100% indicates movement perfectly along the straight-line path. The Bases and Chase tasks (administered without AF, minimising any practice effect) were used as assessment tasks.

These three variables were selected since they are key aspects of most upper-limb tasks. Further, they are commonly impaired following TBI, yet difficult to quantify in normal rehabilitation (Chua, et al., 2007). Reaching accuracy, speed, and smoothness are presently addressed in OT (e.g. during ADL activities), and are typically measured by observation assessments (Marcil, 2007).

Collection of Normative Performance Data

It was important to establish performance benchmarks on the system by assessing non-impaired adults. Normative data (for accuracy, speed, and efficiency) provides a reference point for assessing severity of impairment among TBI participants, for monitoring change, and for setting realistic performance goals during training. Forty healthy adults (32 men, 8 women) participated in the norming (mean age = 29 years; range: 25 to 45 years). All were right hand dominant. They were asked to perform the Bases and Chase tasks without AF. These were selected since they were the assessment tasks used with TBI participants. The results are presented in table 4.2. Gender differences were not evident so combined data are presented.

Table 4.2.

Norm performance for system measured variables (N = 40).

Variable	Left hand Mean (*SD*)	Right hand Mean (*SD*)
Accuracy (percentage)	85.3 (3.6)	84.0 (3.7)
Speed (m/s)	0.26 (0.03)	0.25 (0.03)
Efficiency (percentage)	95.8 (3.5)	95.0 (4.6)

Selection of Movement Variables as the Focus of Treatment

The general aim with all participants was to improve their accuracy, speed, and efficiency scores. However, if they demonstrated greater deficits in a specific variable (based on *SD*s difference from the norm mean), it would be a focus for training. For example, if speed was 2*SD*s below its norm, yet accuracy and efficiency only 1*SD* lower than their norms, speed would a greater focus for treatment.

Augmented Feedback

The main therapeutic tool in the Elements system is the provision of movement feedback, using both AF and KR provided via feedback plots (the latter outlined subsequently) (Todorov, Shadmehr, & Bizzi, 1997). AF is the provision of information over and above the normal (intrinsic) flow of visual and movement feedback (VanVliet & Wulf, 2006). AF is thought to enhance the quality of multimodal feedback available to the performer as they endeavour to re-establish motor control and function. AF enables them to learn the systematic co-variation that occurs between motor-command signals and their effects on the body. This is a vital component of predictive control. Performers can better appreciate their position in the action space, determine what variations in movement parameters are needed to realize a goal, develop a feel for the unfolding movement trajectory itself, and, refine motor planning and forward control of movement.

Conventional (or non-VR) rehabilitation studies have found AF to be effective. For example, AF has been used to improve stroke participants' reaching speed and accuracy (Maulucci & Eckhouse, 2001). This study tracked stroke participants' reach trajectory during a reach to touch task, using a sensor attached to their hand. An auditory sound was produced as AF when the trajectory was outside the normal range (the normal path was established through trials among non-disabled participants). Their participants were tested in one of two conditions: with and without AF. While both groups improved significantly in reaching speed and accuracy, the AF group improved more than the practice group (see (Armagan, Tascioglu, & Oner, 2003) as another example of AF in rehabilitation).

The provision of AF in VR-rehabilitation has been successful in previous studies (e.g. (M. Holden, Dyar, et al., 2001; Piron, et al., 2004)). These systems have focused on using a teacher-animation to guide participants' movements, and provide AF. Though this approach has merit, we contend that using both AF and KR as movement feedback will enhance participants' capacity to acquire motor control and functional skill and to display generalisation. This contention is in line with literature recommending the use of both AF and KR in motor training (Hinder, Tresilian, Riek, & Carson, 2008) and rehabilitation (Mastos, et al., 2007; VanVliet & Wulf, 2006).

AF in the Elements System

AF in the Elements program served three purposes. Firstly, it provided participants with additional knowledge of their actions to aid future movement planning. Secondly, it allowed them to focus their attention externally on the effects of their movement during the tasks. This is a commonly used (and effective) practice in sport science and training (Wulf & Prinz, 2001). Finally, AF promoted a sense of multimodal space and of the spatial relationship between the participant and the objects. This was achieved by providing correlated sensory input during movement. The primary AF features were designed to map onto the three (measured) aspects of performance, accuracy, speed, and efficiency. Thus, the AF used during a task depended on the variables targeted for improvement (see Table 4.3 for the AF features). The additional AF also responded to participants' movements in the VE, providing movement feedback. However, these were not specifically linked to the movement variables.

As discussed previously, environmental enrichment is related to AF. An enriched environment not only promotes motor control, but engages an individual's attention and imagination (Puurunen & Sivenius, 2002). Providing environmental enrichment is a central advantage to VR-rehabilitation (David Rose, et al., 2005), and can significantly improve motor recovery (Grealy, Johnson, & Rushton, 1999; Semlyen, et al., 1998). Therefore, the AF in Elements was also intended to provide environmental enrichment during the training.

Table 4.3

AF features in the Elements system.

Primary AF	Movement feedback associated with AF
Object trace As the object is moved above the screen, a fading trace follows its path on the monitor.	Visual representation of movement *efficiency* variable.
Disk animation As the object is moved, a white circle (the size of the object) is viewed on the screen, moving below it.	Informs the participants on the object's position relative to the targets. Used to inform movement *accuracy*.
Sound pitch and volume for speed Movement speed is also correlated with a sound; here pitch and volume can be selected to increase with speed.	Reinforces the movement trajectory, and *speed*.
Additional AF	
Luminescence Aura effect for proximity to target As the object approaches the correct target, a waxing 'aura' appears around the target	Communicates correct movement choices.
Aura sound effect and placement sound a) As the object approaches the correct target, a 'hover' tone is played, and increases in volume as they approach the target b) A final 'click' sound is emitted when the object is placed on the target.	Also indicates correct movement choices, and reinforces placement.
Ripple effect for placement When the object is placed on the target, a water ripple animation emanates from that location.	Informs participants where the object was placed.

Introducing Participants to AF

To introduce participants to the AF, free exploration was conducted in session 1. Participants were given all AF, allowing them to experience how it related to their own movement, and actively discern how to use it. This process is consistent with theories of active learning, which maintain that effective learning occurs through a process of trial and error, rather than being given the solution (see (Kruschke, 2008) for discussion).

Following free exploration, if needed, the participant's attention was guided to how the AF related to the movement variables (speed, accuracy, efficiency). This was done using open-ended questions - for example: 'describe to me how the sound effect changes as you move the object at different speeds'. The connection between the AF and the movement variables was explained further if the participant still did not understand.

Selection and Application of AF

Selecting which AF to provide during the tasks was done in collaboration with the participant. This decision was informed by observing the participant, and asking which forms of AF they found helpful. If deficits were noticed in a specific movement capacity (based on comparison to the norm data), the relevant AF was introduced to help performance (see Table 4.3). Thus, during training participants were instructed to focus on the AF appropriate to their movement targets. For example, if accuracy was targeted they focused on the disk AF, using it to line the object up before placing it.

Goal Setting

Goal setting is considered an essential part of TBI rehabilitation (Siegert & Taylor, 2004). The aim is for the therapist and participant to decide on a series of end points to achieve through their therapy (Dixon, Thornton, & Young, 2007). Research has shown that patients who had specific rehabilitation goals demonstrated significantly greater improvements than those without (Ponte-Allan & Giles, 1998). Goal setting is thought to benefit rehabilitation by improving participants' motivation, and promoting overall self-efficacy, and wellbeing (see (Siegert & Taylor, 2004) for discussion). Accordingly, goal setting was included as part of the Elements training.

However, while goal setting can benefit rehabilitation, failure to attain goals can be deleterious to the process (Holliday, Ballinger, & Playford, 2007). Good rapport between the therapist and participant is recommended to keep participants positive, and focused on the improvements they have made rather than any unattained goals (Holliday, et al., 2007). Thus, during the Elements training development of rapport with the participants was crucial.

Goal Setting in Elements

Goal setting was driven by the therapist, since participants may not be able to set appropriate goals. Participants were aware of their goals, and progress in meeting them. The general aim was for them to improve their scores on accuracy, speed and efficiency. Thus, participants had goals set for every third session for the three variables. These goals were increased slightly each week. As with the decision of which performance variables to focus on, goal setting was participant specific.

Research has indicated that giving participants consistent, numeric KR benefits rehabilitation, and goal achievement (Holliday, et al., 2007). Thus, KR feedback via data plots (referred to as 'feedback plots' hereafter) was provided each session following the goal-based tasks, prior to the exploratory VE (or assessments). The participant's results were presented on line-graphs depicting performance by session. The three system variables were graphed, with each hand plotted separately. This feedback was designed to improve participants' motivation, understanding of their movement outcomes, and progress in attaining their goals. Figures 5.1- 5.6 are examples of the plots participants were shown (though participants' feedback plots were of raw data only).

Summary of Chapter 4

Chapter 4 described Elements' theoretical basis, hardware, software, and administration procedure. The ITE model of motor control was the theoretical basis for the program. This theory posits that functional movement arises from a balanced interaction between the individual, the task at hand, and the action environment. Thus, we aimed use VR to vary task and environmental factors to account for users' individual limitations, and promote functional movement. The system itself includes two kinds of interaction to challenge and engage participants (goal-based and exploratory), and assessment features (tracking movement accuracy, speed, and efficiency). The main therapeutic tool in the Elements training, AF, aims to develop motor control by providing additional visual and auditory feedback. Participants were also informed of their performance and goal achievement via feedback plots depicting their performance by session.

The Elements system was designed to be used in conjunction with established therapies. Indeed, systems intended to replace in-vivo training with VR have been impractical, with poor usability (Edmans, et al., 2004; Pridmore, et al., 2004). In general the effects of VR alone have not exceeded those of traditional methods (Piron, et al., 2007; Piron, et al., 2003). Two studies were conducted to assess the Elements system's performance with TBI participants undergoing traditional rehabilitation. Chapter 5 presents a multiple case-study, and a within-group comparison is described in Chapter 6.

CHAPTER 5

STUDY 1: CASE-STUDY EVALUATION

STUDY 1: CASE-STUDY EVALUATION

Introduction

Health-science research typically utilizes large sample group comparisons for testing treatment effects. However, single participant case-studies may be preferable when testing new interventions, or investigating treatment effects at an individual level, as in this initial trial of the Elements system (David, 2007).

Case-studies compare change in dependant variables (DVs) for a single participant under varying treatment conditions. There are three variations on this design (Kinugasa, Cerin, & Hooper, 2004). Descriptive case-studies do not systematically investigate the effects of a single intervention (Fisher & Ziviani, 2004). Rather, they subjectively describe a specific case, and investigate multiple treatments. Exploratory case-studies investigate the effects of an intervention across multiple DVs, using descriptive quantitative and qualitative data. Explanatory case-studies investigate outcome effects using statistical analyses, and employ either single subject, or randomized trial designs. Thus, the explanatory method is considered the most rigorous (Backman & Harris, 1999) and was applied in this investigation.

Advantages and Criticisms of Case-study Methodology

While it can be argued that case-study methodology lacks generalisability due to small sample size (Morgan & Morgan, 2001), advocates argue otherwise, since the theoretical basis for treatment is still being assessed (Yin, 1999). Furthermore, case-studies may provide more clinically relevant data, since they gauge the treatment effect for a single participant (as in a clinical setting) rather than a group mean (Kinugasa, et al., 2004).

Case-studies also require fewer participants, thereby minimising recruitment and administration costs (Kinugasa, et al., 2004). This is beneficial when investigating new treatments, since funding and ethical support may be limited. Fewer participants also makes case-studies far easier to replicate (Altman, et al., 2001). The repeated measures nature of case-studies also controls threats to internal validity from systematic differences (e.g. age, gender) between groups (Morgan & Morgan, 2001).

Application of Case-study Design in TBI Research

Case-study designs have been successfully applied in TBI research (Morgan & Morgan, 2001). For example, a single participant case-study used Partial Weight Support (PWS) training to significantly improve ambulation of a TBI patient over 4.5 months

(Scherer, 2007) (see (Arco, 2008; Hardy, et al., 2007; Pachet, Friesen, Winkelaar, & Gray, 2003; Scherer, 2007; Trovato, Slomine, Pidcock, & Christensen, 2006) for further examples of successful case-study research among TBI patients). As described in the systematic review (Chapter 3) the majority of VR-rehabilitation investigations have been case-studies. However, they used questionable methodologies. For example, only two studies employed an AB time-sequence design (Broeren, Bjorkdahl, Pascher, & Rydmark, 2002; M. Holden, et al., 1999). Thus, based on the advantages to case-study methodology, and its previous use among TBI populations, this design was applied in the initial evaluation of the Elements system.

Aims and Hypotheses

The aim of this study was to evaluate a new upper-limb VR-rehabilitation system among TBI patients by conducting a series of single participant case-studies, using and ABA time-sequence method, with multiple-baselines. Specifically, it was predicted that following a 12-session course of VR-rehabilitation, concurrent with normal therapy, participants' upper-limb function would improve compared to baseline performance.

Method

Participants

Three participants with TBI were invited to take part in this study at Epworth Hospital, Melbourne by the Senior Physiotherapist. Because the Elements system can be scaled to the patient's individual skill level, the inclusion criteria were broad. Moreover, at this early stage in the evaluation process, it was not deemed appropriate to test more specific hypotheses about the effects of therapy on different patient sub-groups (e.g., mild vs. severe patients). The inclusion criteria were: under 50 years old, a score of at least two for muscle activity as measured on the Oxford scale (Laycock, 1992) (focusing on wrist/finger flexors/extensors, elbow flexors and shoulder flexors). Each participant experienced deficits in upper-limb function and considered this rehabilitation important (evidenced by their volunteering for the 4-week training program). Participants were also required to have the cognitive capacity to provide informed consent and to understand the VR program (assessment of cognitive capacity was not conducted as part of this research, and this inclusion criteria was judged by the Epworth staff based on routine assessments conducted at the hospital). While there were no prerequisites for visual acuity, the program required a level of vision equivalent to reading a book/magazine, or watching television, which all participants could do. No participants had hearing impairments. These participants were the first three identified by Epworth's physiotherapy team as needing more upper-limb therapy. All consented to participate. Details for each participant follow.

Participant TJ. TJ was a male aged 21 years. His TBI occurred as a result of an automobile collision, 12 months prior to the study and resulted in PTA of 75 days. During this investigation, TJ was first living with family and then independently as an outpatient (the basis for classifying TJ as the most recovered of our three participants). TJ's average score on the Box and Block test (BBT, seen to accurately represent daily functioning ability, described subsequently) during baseline was 73 for his right (dominant) hand, and 51 for his left. These scores were 1.7 and 4.1 *SD*s below the norm for non-disabled participants between 20 and 24 years old. TJ was undergoing physical therapy that mainly targeted balance and gait. He experienced moderate hemiparesis (muscle weakness on one side of the body) and dystonia (sustained muscle contractions/stiffness) in his left arm.

Participant SK. SK was a 20 year-old male who experienced TBI in an automobile collision 8 months prior to the study, with PTA lasting 88 days. SK lived with his family as an outpatient during this investigation. SK's physical therapy consisted of balance retraining, weight-based strength and conditioning, and hydrotherapy swim training. SK's mean right (dominant) hand BBT score during baseline was 39, 5.5 *SD*s below the norm. His baseline BBT mean was 45, 4.9 *SD*s below the norm.

Participant AN. AN was a male aged 20 years. He experienced TBI as a result of an automobile collision 4 years before the study. AN's PTA lasted more than 3 months (exact length of PTA unknown), and he was an inpatient during the study. AN's status as an inpatient after 4 years was due to his accident occurring in a remote setting, several thousand km from any rehabilitation facility. AN had been to several hospitals across Australia, and was admitted at Epworth for an initial assessment which became a six month period of inpatient rehabilitation He presented with ataxia and required assistance to walk. AN underwent physical therapy on a daily basis focusing mainly on mobility and gait, and his upper-limb training was less intensive. AN scored a mean of 27 on the BBT for his right (dominant) hand during baseline. This value is 7 *SD*s below the norm. His left hand BBT baseline mean was 28, 6.9 *SD*s below the norm.

Materials

Elements System Administration

All participants experienced the Elements program and administration protocol detailed in Chapter 4. However, only the goal-based VEs were included. This was to assess their efficacy and inform the final production of the exploratory tasks, and tracking system. Thus, the last 5-10 minutes of each session were used for administering the assessments. Participants' accuracy, speed, and efficiency scores were also used as outcome measures.

Standardised Measures of Functional Skill

Upper-limb function was assessed using two standardised measures. These assessments were included since they have good predictive validity, thus providing information on how participants' performance would translate to real-world situations. The presentation order of the assessments was counterbalanced ensuring participants did not perform them in the same order in two consecutive sessions.

Box and Block Test (BBT). The BBT consists of two connected boxes (each 27cm x 24 cm, with walls 8.5cm high), separated by a vertical wooden barrier (15.2 cm high). One box is filled with 150 2.5cm wooden cubes. The goal is to move as many blocks as possible over the barrier to the other box, one at a time, in 60s using one hand. The BBT has been used successfully among TBI populations (e.g. (Desrosiers, Rochette, Hebert, & Bravo, 1997)), and in VR-rehabilitation studies (e.g. (Fischer, et al., 2007)).

Test-retest reliability for the BBT was assessed among non-disabled populations using two administrations, six months apart. Significant results were found using Spearman's Rho for the left (rho = 0.94), and right hand (rho = 0.98) (Desrosiers, et al., 1997). A follow-up assessment took place with seven days between trials, among 44 participants experiencing upper-limb paresis from stroke, multiple sclerosis or TBI (Platz, Pinkowski, et al., 2005). The results confirmed the high reliability of the BBT (ICC = .96). Platz and colleagues (2005) also assessed inter-rater reliability, with two raters scoring the results for the 44 participants independently. This assessment produced an ICC of .93.

The BBT also demonstrated good predictive validity with other measures. Correlations of .91 were found between the BBT and the Placing subtest of the Minnesota Rate of Manipulation test (Platz, VanWijck, & Jonhnson, 2005). The BBT correlated significantly with the ARAT in two studies (r = .82 (Herbet, Carr, & Bilodeau, 1988), and .95 (Platz, Pinkowski, et al., 2005)), with the FMA (r = 0.92), the Motricity Index (r = .798)

(Platz, Pinkowski, et al., 2005), and grip strength ($r = 0.87$) (Boissy, Bourbonnais, Carlotti, Gravel, & Arsenault, 1999). Finally, the BBT's face validity is evidenced by its sensitivity to changes in arm function of disabled populations over time (Broeren, et al., 2002; Fischer, et al., 2007; Jang, et al., 2005; Stewart, et al., 2007).

McCarron Assessment of Neuromuscular Dysfunction (MAND). The theory of task-specificity indicates that minimal improvement in bimanual coordination is likely from unilateral training (Waller, et al., 2008). Yet, previous research has documented some improved bimanual arm function following unilateral rehabilitation (Eastridge & Mozzoni, 2005; Waller, et al., 2008). Accordingly, our study used two tasks assessing bimanual dexterity from the MAND battery. For the *nuts-and-bolts* tasks, participants hold a metal nut in their non-preferred hand and screw either a large or small bolt into the nut as quickly as possible with their preferred hand (there is no upper time limit for the task). The *bead-threading* task requires participants to hold a metal rod in their non-preferred hand and thread as many wooden beads as possible onto it in 30s. These MAND tasks are recommended for use with TBI populations, and have demonstrated good individual reliability and validity (McCarron, 1997).

The nuts-and-bolts and bead threading tasks showed excellent test-retest reliability (assessments one month apart; $r = .97$, .92 respectively) among 31 neurologically impaired participants (McCarron, 1997). Further, the MAND's content validity is evidenced by its foundation on previous clinical research, and functional assessments. Accordingly, its tasks are deemed appropriate for assessment of motor function among TBI patients (McCarron, 1997). Finally, scores on the MAND have been significantly correlated with participants' work capacity ($r = .70$) one year after assessment, demonstrating the measure's predictive validity.

Procedure

Design of Case-studies

An ABA time-sequence design, with multiple baselines between participants was used in this study. The first baseline phase (A1) consisted of an initial series of assessments of upper-limb function (VR-system variables and standardised measures). This phase lasted four sessions for TJ, seven for SK, and nine for AN. The length of the A1 phases was based on recommendations of at least three data points in the baseline phase (Morgan & Morgan, 2001). Accordingly, A1 lengths of four, seven, and nine were sufficient to establish the participants’ baseline performance. Moreover, the multiple-baseline design requires varying baseline times between participants to gauge a temporal relationship between the initiation of treatment and improved performance (Backman & Harris, 1999). In our study the A1 lengths represent participants’ level of recovery, with TJ (the most recovered) requiring a shorter A1 time to establish his level of performance, then SK had the second longest (seven sessions), and finally AN had a nine session A1 phase.

The intervention phase (B) was comprised of the 12 60-minute VR-sessions, conducted over four weeks. Performance was assessed at the conclusion of each session. Following the B phase a second baseline (A2) was conducted. The purpose of the A2 phase was to assess whether improvements made during the B phase persisted after cessation of training. This phase consisted of five sessions for TJ and AN, and six for SK (the A2 phase was intended to be six sessions for each participant, however TJ and AN were absent for one session). All testing was conducted onsite at the Epworth hospital.

Data Analysis

Research has demonstrated that relying on one method in case-study data analysis is unreliable (Nourbakhsh & Ottenbacher, 1994). Therefore, multiple analytic procedures were applied presently. First, visual inspection of time-sequence plots (based on smoothed data) was conducted. Then, two-standard deviation (2*SD*) band, or split-middle trend analyses (SMTA) were used to assess statistical significance. Finally, clinical significance of the BBT results was calculated using the Jacobson-Truax (JT) method.

Visual inspection of smoothed data. In case-study research the most common analysis method is visual inspection of time sequence plots (Kinugasa, et al., 2004; Morgan & Morgan, 2001). This entails plotting the independent variable (IV) along the X-axis, and the DV on the Y-axis of a segmented line graph, then visually assessing changes in performance between phases. In the present study, each time-sequence plot used sessions as the IV, and the outcome variable as the DV. The X-axis was divided by vertical lines to distinguish the baseline and treatment phases. These time-sequence plots were then sight inspected to assess for any change in the DV between the A1 and B phases. Subsequently, performance between the B and A2 phases was compared. A positive treatment effect would be denoted by improvements in the B phase, followed by maintenance of scores during A2.

However, a limitation to visual inspection is natural variability in the data masking the treatment effect (Sideridis, 1997). Accordingly, data smoothing procedures can be applied to reduce this variability, and highlight performance trends. In this study exponential data smoothing (EDS) was used (Sideridis, 1997). This method provides more accurate results than others (such as simple moving average smoothing) since more recent data points are given greater statistical weight in calculating smoothed values (see (Sideridis, 1997) for discussion). Accordingly, the weight put on previous data points is determined by the α value used in the EDS formula (between 0 and 1). Larger α values assign greater weight to more recent observations. The EDS formula is:

$$Y_{t+1} = \alpha S_t + (1-\alpha)Y_t$$

where Y_{t+1} is the smoothed value, S_t is the previous observed value, Y_t is the previous smoothed value, and α is the smoothing constant (Sideridis, 1997). The α value used in calculating each EDS set is the one that results in the smallest total mean difference between the smoothed data points and the actual values.

2SD band analysis. For data with a flat or negative trend in the A1 phase 2*SD* band analysis was used to assess statistical significance. This method is based on calculation of the mean and *SD* of the baseline data (Nourbakhsh & Ottenbacher, 1994). Once these values are obtained, if at least two consecutive points in the B phase are above the two *SD* mark, a significant improvement ($\alpha < .05$) has occurred (Vaz, et al., 2008). However, when baseline data shows a distinct positive trend, the likelihood of Type I error is increased using this method (Nourbakhsh & Ottenbacher, 1994). Accordingly, SMTA analyses were used for results with a noticeable positive baseline trend. This combination of both 2*SD* band and SMTA is consistent with previous TBI case-studies (Vaz, et al., 2008).

SMTA. SMTA involves two stages. First, a best-fit (or celeration) line is plotted through the A1 phase data, with half the points falling on either side of the line (Backman & Harris, 1999) (in this study Excel's 'add linear trend-line' function was used to create the celeration line). Then, the line is projected into the B phase data, and cumulative binomial analyses assess whether a significant number of data points fall above the line (or below, depending on the index of improvement) (Nourbakhsh & Ottenbacher, 1993). In the present study the binomial probability used was .5, and statistical significance was set at $\alpha < .05$. SMTA was not used for variables with declining or stable baseline, since even slight improvements (or maintained performance in the case of a declining baseline) may falsely be deemed significant (Nourbakhsh & Ottenbacher, 1994).

Clinical significance analysis. Clinical significance theory advises against over reliance on statistical analyses in intervention research, since a treatment may not generate statistically significant results, yet the patient finds it beneficial (the opposite may also occur) (Ogles, et al., 2001). The most effective method of assessing clinical significance is the JT method (see (Atkins, Bedics, & McGlinchey, 2005) for review of clinical significance analyses). This performance-comparison method is intended for N=1 data (Campbell, 2005; Jacobson & Truax, 1991), and involves two stages. Firstly, if the participant improved by two *SD*s pre to post test (based on mean baseline data), they have made 'functional' change. This improvement is then analysed using the Reliable Change Index (RCI) formula, to assess its reliability (Jacobson & Truax, 1991). The RCI formula is (Jacobson & Truax, 1991):

$$\mathrm{RCI} = \frac{x_2 - x_1}{S_{diff}}$$

x_2 represents the final post test score, x_1 is the first pre-test score, and S_{diff} is the standard error of difference between the two scores (see (Jacobson & Truax, 1991) for S_{diff} calculation formulas). RCI scores are considered reliable if they are greater than 1.96. Only the BBT results were assessed for clinical significance, since this was our primary standardised measure, and had sufficient norm and standard error of measurement data.

Results

System-measured Variables

These data were taken from an average of the bases and chase task scores, administered at the end of each session without AF.

Accuracy

The time-sequence plots for accuracy are presented in Figure 5.1. Sight inspection of these graphs indicated improvements for both hands for participants TJ and AN between the A1 and B phases. These improvements were maintained into the A2 phase. SK demonstrated no improvement with his left hand, and the moderate improvement that was evident for his right in later sessions was not maintained into A2. Follow up 2*SD* band analyses indicated significant improvements for participants TJ (right hand *M*(A1) = 77.1, *SD* = 3.8; left hand *M*(A1) = 66.6, *SD* = 3.2) and AN (right hand *M*(A1) = 62.2, *SD* = 4.9; left hand *M*(A1) = 58.4, *SD* = 5.6).

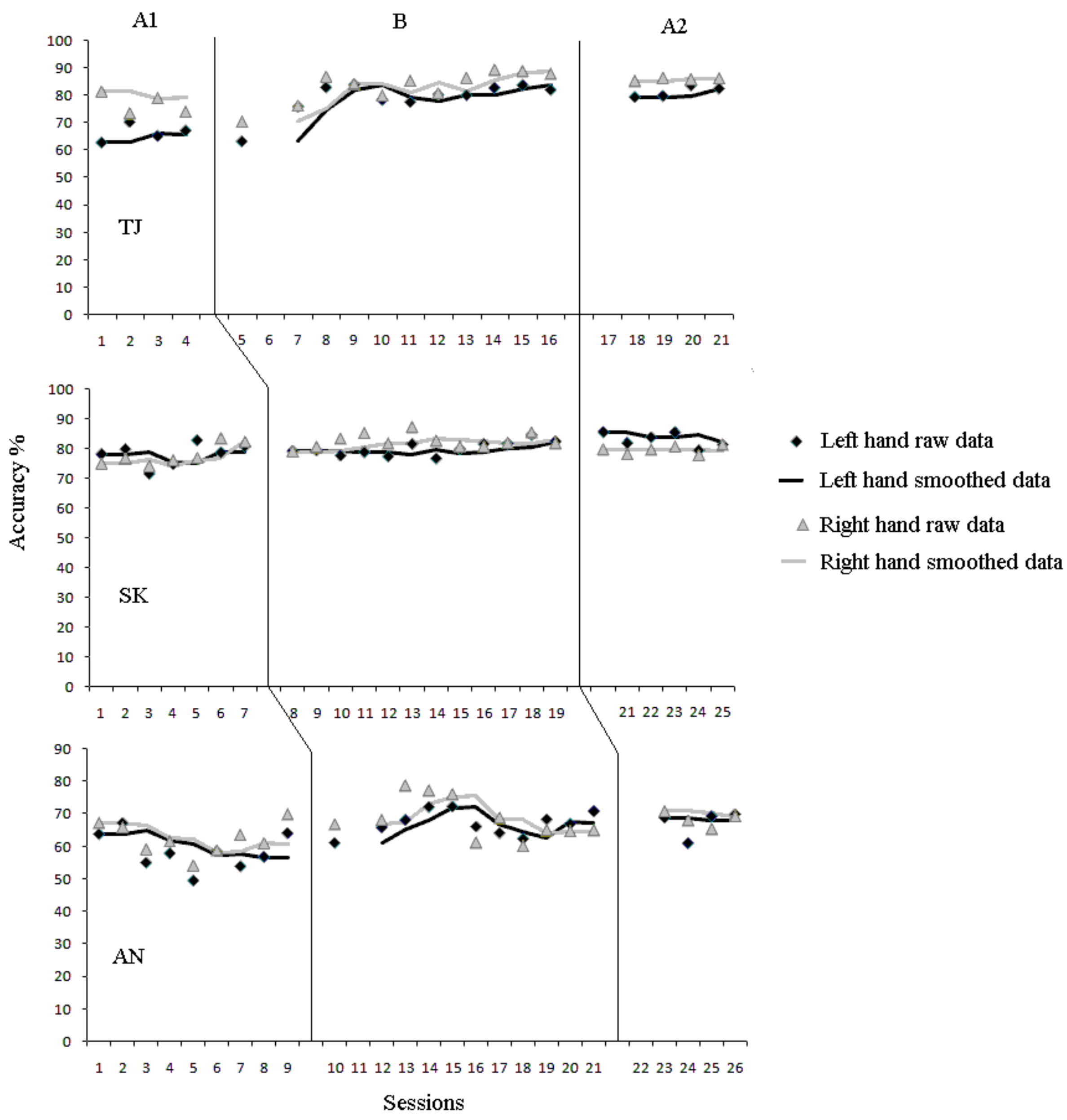


Figure 5.1. Time-sequence graph of accuracy results for all participants.

Speed

Figure 5.2 presents time-sequence plots for movement speed, and the participants demonstrated no improvements here. However, despite a drop off in speed for TJ in the B phase, and to a lesser extent SK (right hand), their performance variability was far less through the A2 phase. Indeed, there was some improvement evident for SK's left hand during A2. Statistical analyses (2*SD* band) confirmed no significant improvements in speed.

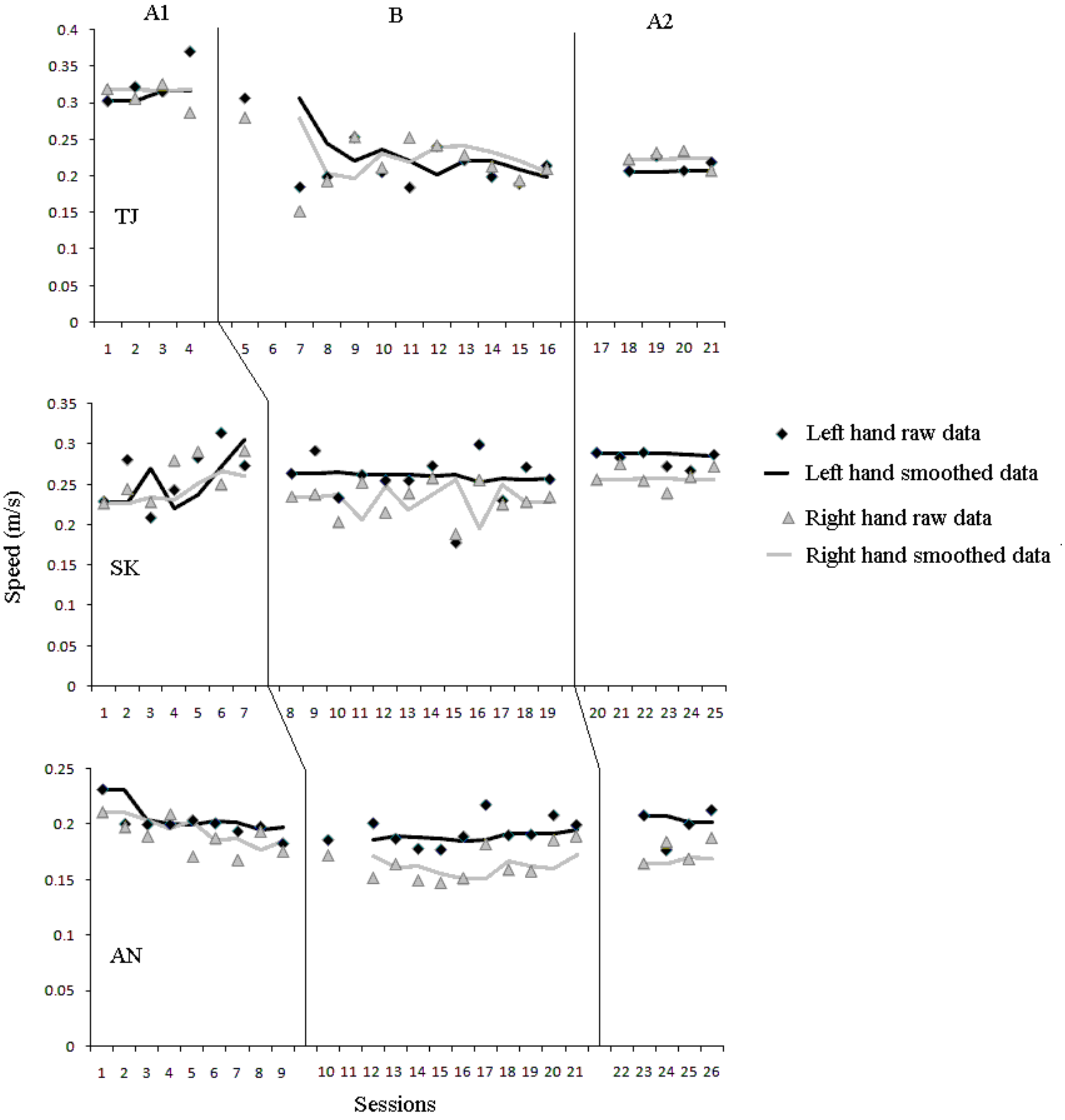


Figure 5.2. Time-sequence graph of speed results for all participants.

Efficiency

Sight inspection of the smoothed efficiency data indicated improved performance between A1 and B phases for TJ's left hand, SK's left and right hands, and AN's right hand. These improvements were maintained into the A2 phase (Figure 5.3). For participant TJ, this (moderate) improvement occurred towards the end of the B phase with both hands. SK and

AN’s performance improved at the beginning of the B phase. Significant results from 2*SD* band analyses were found only for SK’s right hand (*M*(A1) = 83.2, *SD* = 4.4), and AN’s right hand (*M*(A1) = 85.5, *SD* = 2.3).

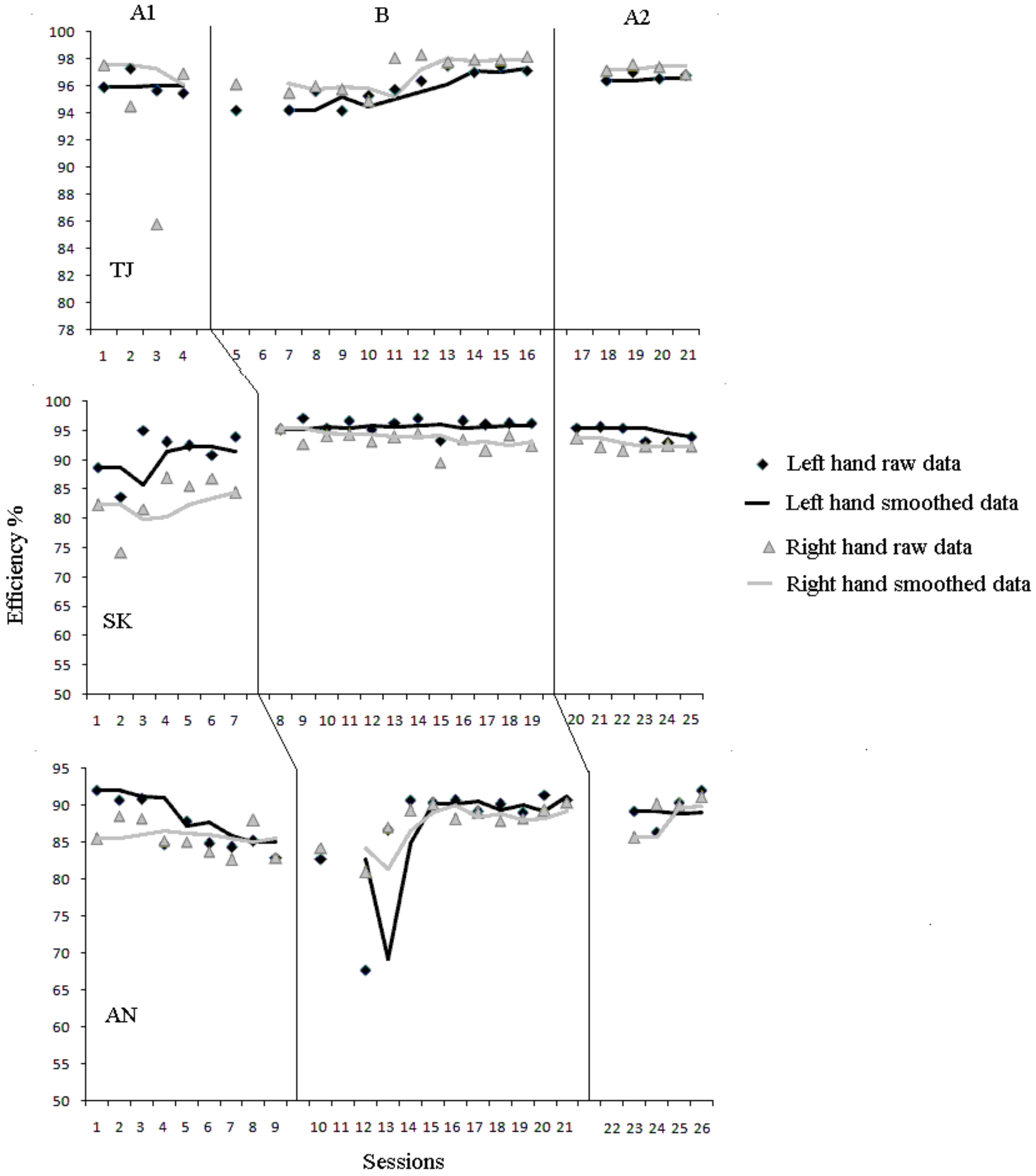


Figure 5.3. Time-sequence graph of efficiency results for all participants.

Standardised Measures

BBT

Sight inspection indicated that TJ and SK moved more blocks with their left and right hands in the B phase compared to A1, and maintained that improvement into A2 (see Figure 5.4). AN demonstrated improvement in the B phase for his left hand only, which was maintained into A2. Given the clear upward trends in some baseline performances on this test, SMTAs were applied. These showed that the improvements between baseline and treatment were not significant for TJ's right hand (N = 12, $p = .99$), or SK's left hand (N = 12, $p = .99$). Significant improvements were found from 2*SD* band analyses for TJ's left hand (*M*(A1) = 51.3, *SD* = 3.4), SK's right hand (*M*(A1) = 39.7, *SD* = 3.0), and AN's left hand (*M*(A1) = 28.1, *SD* = 1.5). Clinical significance analyses indicated that TJ's improvement on both hands were functional and reliable (RCI = 14.14 for his right hand, 10.61 for his left). Similarly, both SK's left and right hand results were found to be functional and reliable (RCI = 5.30 for his right hand, 9.28 for his left). Finally, AN's left hand results were deemed functional, but not reliable.

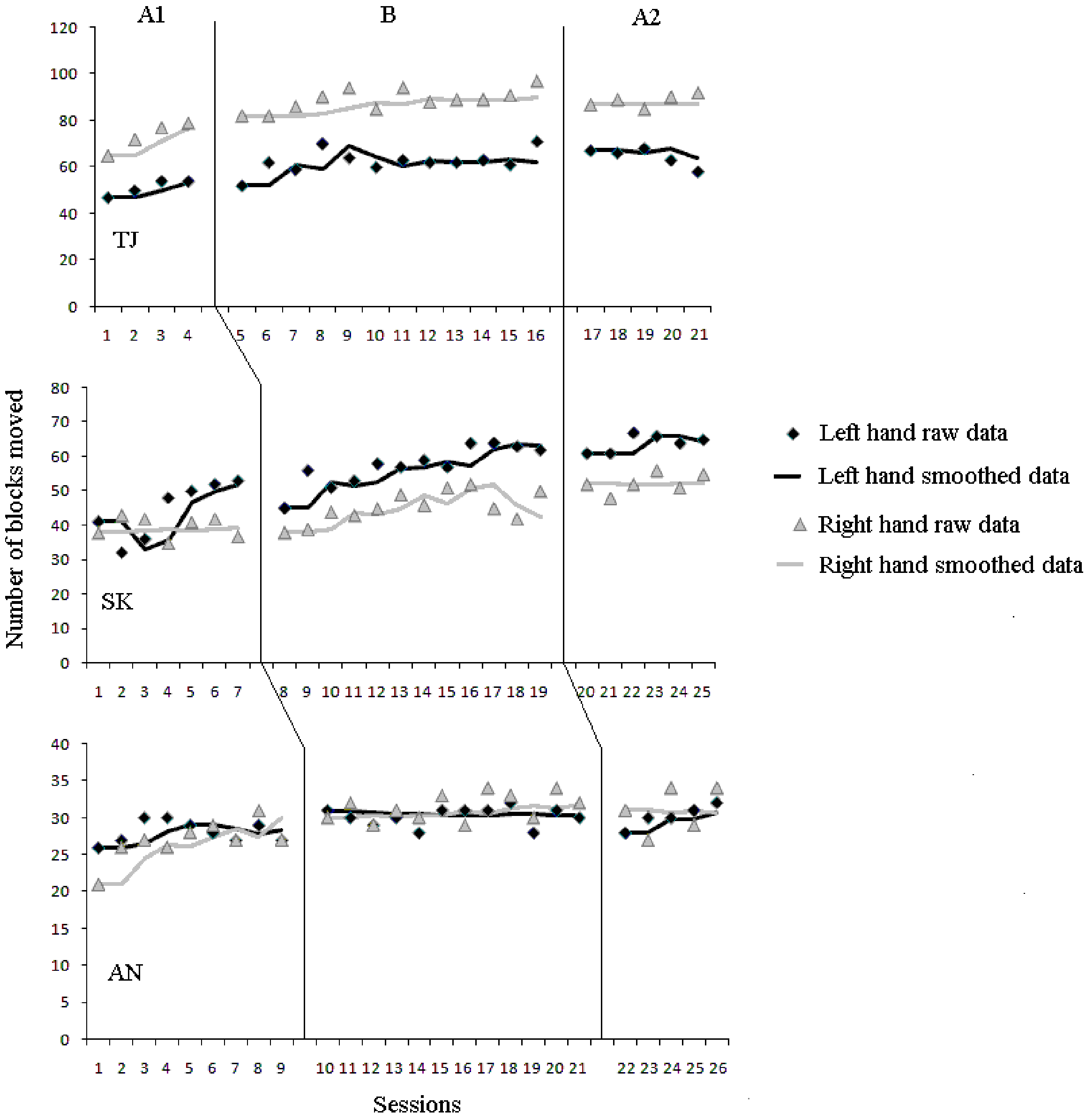


Figure 5.4. Time-sequence graph of BBT results for all participants.

MAND

The time-sequence plots for the MAND tasks showed mixed results. For the nuts-and-bolts (Figure 5.5), marginal improvements (reduced time to complete the task) were seen for TJ on both versions. TJ's improvement for the small version was maintained into the A2 phase. However, he tended to take longer with the large task in the A2 phase than either of the previous phases. Participant SK showed improvement toward the end of the B phase for both tasks, which continued into A2. AN showed no reduction in time for either task during or after treatment. Significant improvements were confirmed by 2*SD* band analyses for participant TJ on the large version only (*M*(A1) = 17.2, *SD* = 1.4).

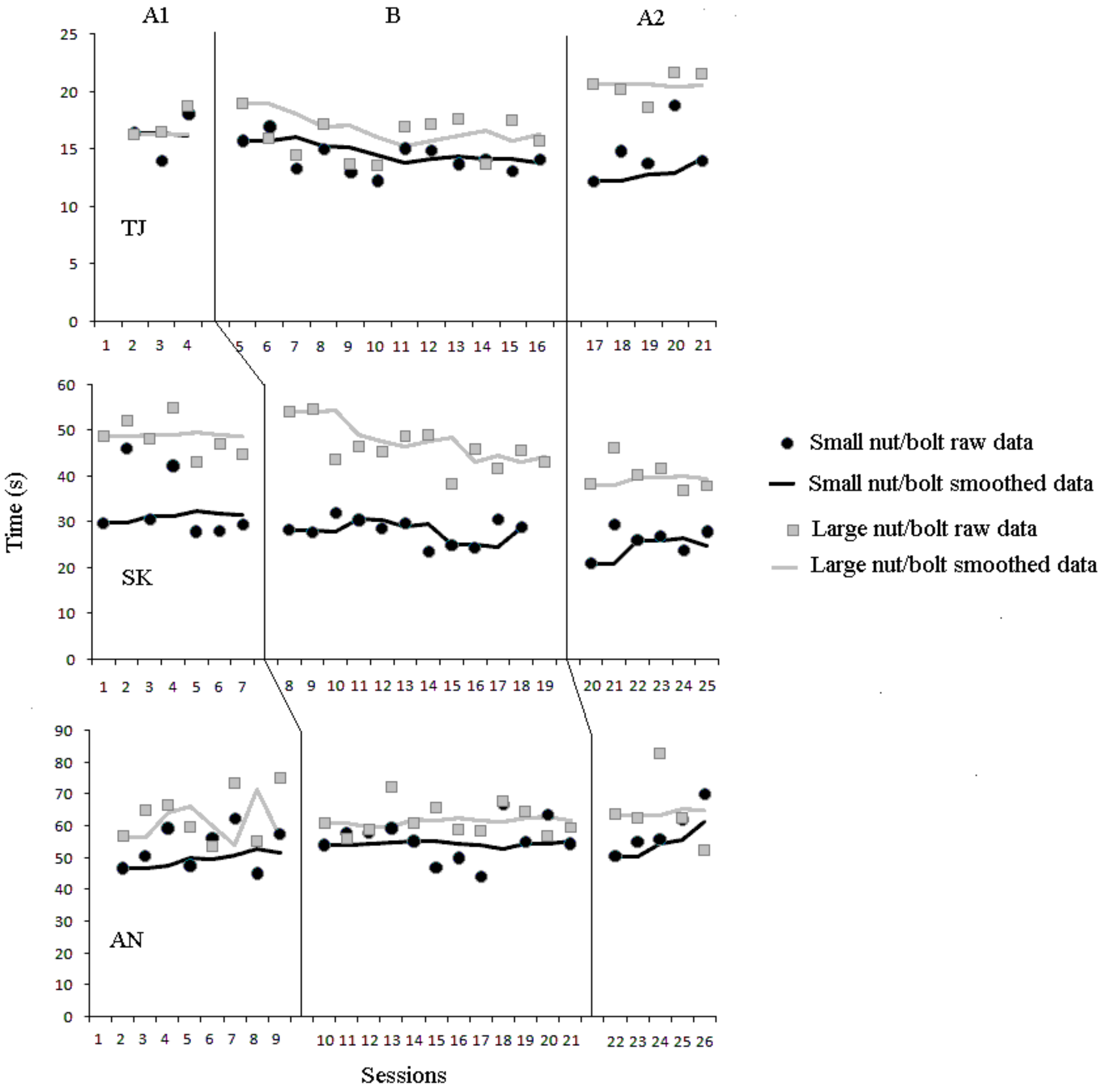


Figure 5.5. Time-sequence graph of nuts-and-bolts results for all participants.

For the bead threading task, some improvements in performance were visible for participants TJ and SK in the B phase, and A2 scores were increased compared to A1 levels (Figure 5.6). AN did not improve during the B phase. However, his A2 scores were less variable and exceeded those from the previous phases. Accordingly, 2*SD* band analysis indicated significant improvements for TJ (*M*(A1) = 13.7, *SD* = 0.6) and SK (*M*(A1) = 9.4, *SD* = 0.8). These results, and the others presented above, are summarized in Table 5.1.

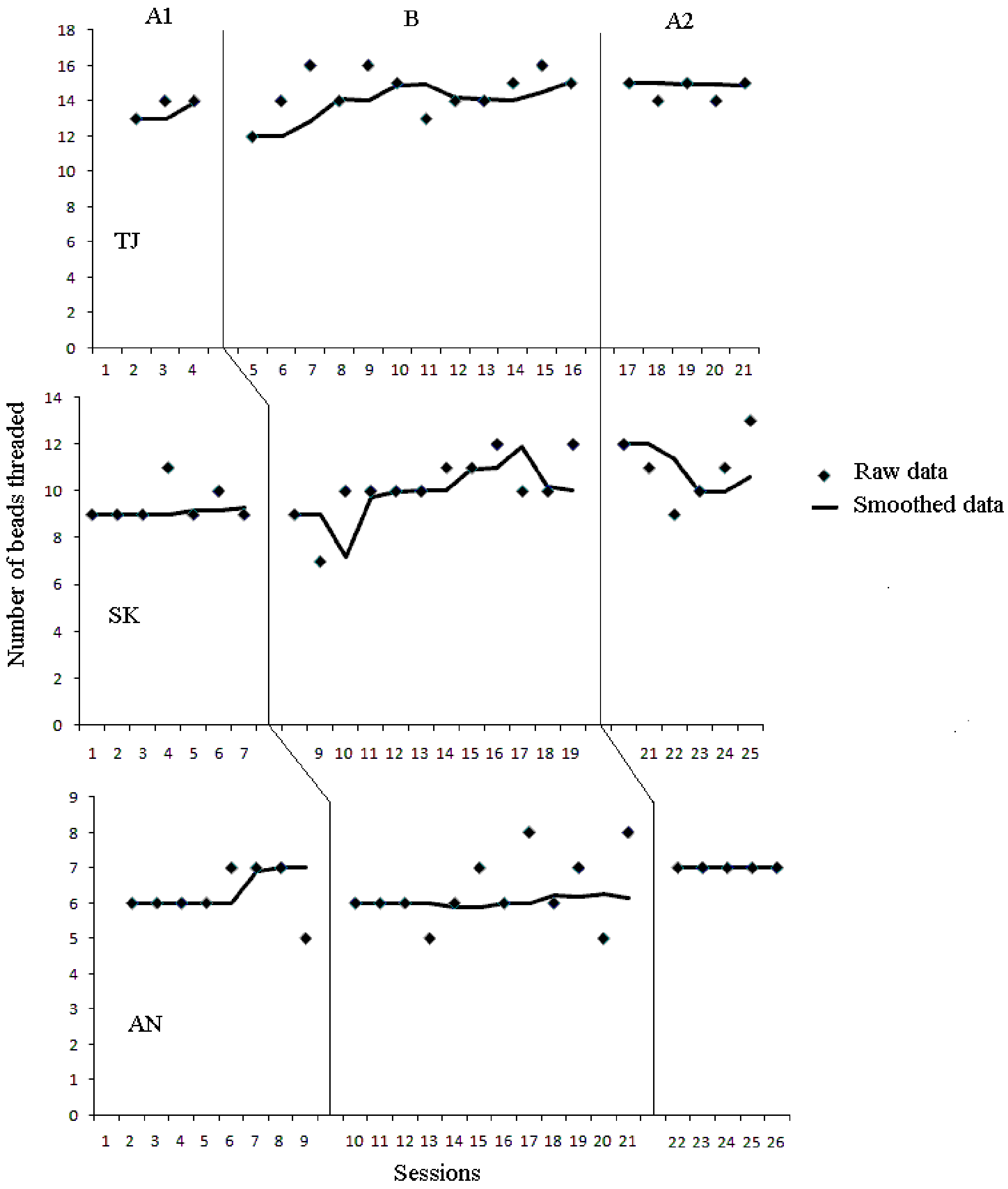


Figure 5.6. Time-sequence graph of bead-threading task results for all participants.

Table 5.1.

Summary of Case-study Results.

Variables	Participant	Change Analysis			
		A1 to B phase		B to A2 phase	
		Left hand	Right hand	Left	Right
Accuracy	TJ	↑*	↑*	**M**	**M**
	SK	**NC**	↑	**M**	↓
	AN	↑*	↑*	**M**	**M**
Speed	TJ	↓	↓	**M**	**M**
	SK	**NC**	↓	↑	**M**
	AN	**NC**	↓	**M**	**M**
Efficiency	TJ	↑	↑	**M**	**M**
	SK	↑	↑*	**M**	**M**
	AN	**NC**	↑*	**M**	**M**
BBT	TJ	↑*fr	↑fr	**M**	**M**
	SK	↑fr	↑*fr	**M**	**M**
	AN	↑*f	**NC**	**M**	**M**
MAND – nuts/bolts	TJ	Small: ↑	Large: ↑*	S: **M**	L: ↓
	SK	Small: ↑	Large: ↑	S: **M**	L: **M**
	AN	Small: **NC**	Large: **NC**	S: **M**	L: **M**
MAND - Beads	TJ	↑*		**M**	
	SK	↑*		**M**	
	AN	**NC**		↑	

Notes:

↑ **-** Performance improvements noted from visual inspection of EDS data

NC - No change from visual inspection of EDS data

↓ **-** Performance decline from visual inspection of EDS data

M - Score maintained between B and A2 phase from visual inspection

* - denotes significant improvement at .05 level using the 2SD band method

f - denotes functional improvement

r - denotes reliable improvement

Discussion

The aim of the present study was to evaluate the effectiveness of a new VR-system for upper-limb rehabilitation of individuals with TBI. These case-study results generally support the efficacy of the system at two levels: system-measured performance and functional skill. Using multiple baselines across participants, we showed a relationship between the timing of the treatment and levels of performance for several DVs. These treatment effects were evident despite all participants continuing conventional therapy, and were largely maintained in the A2 phase. Performance trends are discussed in more detail below.

System-measured Variables

At the beginning of the study, TJ's hand function was generally well rehabilitated. He scored highly on the speed and efficiency variables but his accuracy scores were relatively low during A1. Therefore, his goal was to improve accuracy while maintaining acceptable speed and efficiency. This objective was achieved despite an initial decline in speed early in treatment. Overall, his pattern of change suggests improvement in motor control, mirrored by improved efficiency (though not statistically significant). TJ's results in the B phase were also maintained into A2, which is indicative of motor learning.

Participant SK's progress on the system-measured DVs was the most variable. He appeared to take longer to engage with the therapy, which may explain his relatively late improvement in accuracy compared to AN and TJ. Nonetheless, SK demonstrated the most notable improvement on efficiency. This suggests that the trace AF may have been used preferentially to assist in his movement planning. SK commented on how he could 'imagine the trace' during the assessment tasks (where no AF was present) to help guide his movement path. In sum, SK's efficiency results tend to support the theory that AF provided in a graded series of VEs can result in benefits to motor control.

Participant AN showed significant improvement on both left and right hand for movement accuracy. During the A1 phase and the start of the intervention AN's movement of the object during transport was fast, but his terminal control was less developed, causing poor accuracy scores (50 - 60% during A1). His accuracy toward the end of training was around 70%, with no decline in speed. This finding indicates improvements in motor control. Based on the documented trade-off between speed and accuracy in reaching (Schmidt & Lee, 1999), we might expect improvement on one of these variables at the expense of the other, but this was not the case. This trade-off between speed and accuracy is a central tenant of Fitts' Law (see (Schmidt & Lee, 1999) for review, and (Fitts, 1954) for original research). And, research has indicated that the extent of this trade-off may vary between populations, which may be relevant to further TBI research. This issue is discussed further in Chapter 6. AN also improved significantly on efficiency for his right hand, suggesting his overall movement patterns became smoother. Maintenance of these improvements into the A2 phase again suggests stability in the organization of movement patterns. Notably, participants tended to focus on improving their accuracy, since this was the most obvious deficit during baseline. A different pattern of change may result in other cases where speed or efficiency are targeted for improvement.

Standardised Measures of Functional Skill

Participant TJ showed improvements on the (large) nuts-and-bolts test, the beads task, and BBT (left hand). For the large nuts-and-bolts test, TJ's slower performance during A2 indicates that while he was able to improve his bimanual movements, he reverted to an earlier movement pattern during A2. SK's right hand BBT and beads task results all showed significant treatment effects. So too did AN's left hand BBT scores. Taken together, these findings support the efficacy of the Elements system in training aspects of object manipulation and control, since improvements were noted for each participant. However, because not all changes were statistically significant, a longer course of VR-rehabilitation may be needed to consolidate improvements and functional skills.

The absence of significant improvements on the small nut-and-bolt task indicates that the course of training had only minor effect on more fine-grained control of the fingers. However, these results may mask a general training effect. It is possible that fine manipulative skills were undergoing a period of re-organization due to the intervention, but new movement patterns were not yet established. Again, further research with a longer training schedule is needed to investigate these more subtle learning effects.

General Discussion

Findings here demonstrate that providing AF using a series of graded tasks in a VE may facilitate motor learning in TBI, and are consistent with other (non-VR) AF research (Armagan, et al., 2003; Eastridge & Mozzoni, 2005; Maulucci & Eckhouse, 2001; Platz, et al., 1999; Platz, et al., 2001).

The Elements system's AF provided information over and above the normal flow of visual and movement feedback (VanVliet & Wulf, 2006). Specifically, it is theorised that although AF increases the amount of stimuli in the environment, it reduces the overall cognitive load by highlighting relevant information. Further, it provides a multi-modal understanding of actions in the environment (Hartveld & Hegarty, 1996). The AF was also designed to help participants focus their attention on the external effects of their movement—a commonly used practice in sport science and training (see (Wulf & Prinz, 2001) for review). Research on normative and TBI populations has demonstrated that development of motor skills progresses from slow, consciously controlled movements to more rapid, autonomous action (Hubert, et al., 2007; Mastos, et al., 2007). During this progression, the performer's attention shifts from internal to external focus (i.e., toward the effects of their movement rather than its biomechanics). Participants with TBI often find the transition to so called automatic control difficult. We argue that by prompting participants to focus their attention externally, the transition may be enhanced (Wulf & Prinz, 2001). However, the precise nature of this effect is in need of further research.

The Elements VEs placed progressively greater demands on motor planning, while maintaining a common set of movement goals. The cognitive deficits associated with TBI underpin their difficulties in motor planning (Gentleman, 2001). Based on ecological approaches to movement (with interacting *individual*, *task*, and *environmental* constraints (Shumway-Cook & Woollacott, 2007)), we argue that the performance effects we observed were due to cognitive change at the level of movement planning. These improvements were facilitated by scaling the difficulty of the training tasks and provision of AF. The latter reinforced the performer's knowledge of the relationship between their movement command signals and their resultant effects on the body. This knowledge is central to predictive motor control, and AF of the type provided here is regarded as a means of training internal modeling (Shumway-Cook & Woollacott, 2007).

Those measures that showed mixed training effects generally involved some form of bimanual coordination, specifically the MAND tasks. This finding is consistent with the task-specificity principle, and earlier research (Seidler, Noll, & Thiers, 2004). Hence, we see a further role for the development of VEs that target bimanual coordination, and predict greater improvements on the MAND tasks given a longer course of therapy. One possibility is incorporating multiple objects (as in the Elements exploratory VEs) into the tasks and setting up affordances for coupled or sequential actions (see (D. Rose & Winstein, 2004; Winstein, Wing, & Whitall, 2003) for discussion on the use of bimanual activities in rehabilitation). Nevertheless, the results we obtained on standardised measures are consistent with VR studies involving stroke patients (Boian, et al., 2002; Fischer, et al., 2007; Gaggioli, et al., 2007; Piron, et al., 2004; Stewart, et al., 2007; Turolla, et al., 2007).

Summary of Chapter 5

The present study demonstrated that the Elements VR system can improve upper-limb function among participants with TBI. The system progressively challenged participants' motor planning abilities, and provided them with specific AF that was correlated to their movement. Although not all results were significant, many still showed improvement trends from visual inspection. Further, the clinical significance analyses yielded positive results for all participants. These findings indicate that participants experienced benefits from the training that resulted in improvements in 'real-world' functioning. Accordingly, based on the positive results of these case-studies, further larger-sample evaluation of the Elements system was justified. Chapter 6 presents the results of the within-groups investigation.

CHAPTER 6

STUDY 2: WITHIN-GROUPS INVESTIGATION

STUDY 2: WITHIN-GROUPS INVESTIGATION

Introduction

In light of the generally positive case-study findings presented in Chapter 5, a follow up within-group evaluation was conducted. This design utilises a single research group who experience all levels of the IV(s). Changes on the DV under the varying conditions are then statistically compared (Bordens & Abbott, 2008).

Advantages and Disadvantages of the Within-groups Design

The within-group design offers some advantages over between-groups and was deemed a more viable choice in this study (Goodwin, 2005). Within-groups offers greater statistical power than between-groups since threats to internal validity from systematic differences between experimental groups (e.g., gender or IQ) are controlled, and more data is analysed (see (Cook & Rumrill, 2005; Mitchell & Jolley, 2007) for discussion). Furthermore, by increasing the number of assessments for each participant the influence of measurement errors, such as fatigue during an assessment, is reduced (Bordens & Abbott, 2008).

For ethical reasons, in many program evaluations of the type presented in this thesis, participants continue their individual therapy while undergoing the new treatment. Given variations in the way this therapy can be administered, differences in rehabilitation methods experienced by the treatment and control groups would likely be a significant confounding variable in a between-groups design. However, a within-groups study can avoid this threat to internal validity (and afford the other advantages discussed above).

One potential limitation of within-groups studies is order effects-- the possibility that experiencing one level of the IV may affect participants' subsequent performance. For example, they may deduce the purpose of the study by experiencing multiple levels of the IV (see (Goodwin, 2005; Mitchell & Jolley, 2007) for further discussion). These order effects (or practice effects) can be minimised by giving participants practice before the treatment, randomising the presentation order of the IV levels, and allowing time between administrations (Goodwin, 2005).

Application of Within-groups Designs in TBI and VR Research

Within-groups designs have been successfully used to study the effect of different cognitive (e.g. (Fleming, Lucas, & Lightbody, 2006; A. Walker, Onus, Doyle, Clare, & McCarthy, 2005)), and movement (e.g. (Shaw, et al., 2005; W. C. Walker & Pickett, 2007;

Wiese, et al., 2004)) rehabilitation on TBI and the natural history of the disorder (Albensi & Janigro, 2003). Furthermore, the majority of research investigating VR- rehabilitation has applied within-groups designs. For example, the Rutgers group's participants underwent 2-4 weeks of VR-training, targeting finger ROM, fractionation, speed, and hand strength (measured by the system). Improvements on these variables between pre and post-test were demonstrated using *t*-tests (Adamovich, et al., 2004) and description of improvements (Boian, et al., 2002; Jack, et al., 2001; Kuttuva, et al., 2006).

Additionally, the Holden, and Piron groups have investigated their teacher-animation systems using within-groups designs. These programs required participants to move real objects with sensors attached to them, and copy actions demonstrated by the teacher-animation (e.g. pouring a water jug (M. Holden & Dyar, 2002), see Chapter 3 for details). Significant improvements in performance between pre- and post-treatment were seen on standardised assessments (e.g. FMA, FIM, WMT) using *t*-tests (M. Holden & Dyar, 2002), Wilcoxon tests (Piron, et al., 2007; Piron, et al., 2005; Piron, et al., 2004; Piron, et al., 2003), ANOVA (M. Holden, et al., 2007), and general description of results (M. Holden, Dettwiler, et al., 2001; M. Holden, Dyar, et al., 2001; M. Holden, et al., 1999). Accordingly these successful within-group studies support the application of this design presently.

Aims and Hypotheses

The aim of this study was to further assess the efficacy of the Elements program by conducting a within-groups evaluation. It was predicted that TBI participants would demonstrate improved upper-limb and neurobehavioral function following VR-training.

Method

Participants

Nine TBI participants (5 males, 4 females) were recruited at the Epworth Hospital, Melbourne. The inclusion criteria and recruitment procedure were identical to those in the case-study investigation (see Chapter 5). The participants' ages ranged from 18 to 48 years, with a mean of 33 (*SD* = 11.2). The median PTA for the participants was 70 days (range 28 to 630 days). Eight of our participants were in the extremely-severe category of TBI and one very-severe (Lezak, et al., 2004). The median time since injury (TSI) was 9 months (range 3-178 months). All participants were right handed prior to their TBI. Two participants experienced hemiplegia on their left side, and one on their right, post-TBI.

Of these participants two were inpatients, two were residents at an assisted living facility, and five were living with relatives. All participants continued their normal rehabilitation, which focussed on weight-based strength and conditioning exercises, gait and mobility rehabilitation, hydrotherapy swim training, OT, and speech therapy. During the eight weeks of the study participants' therapy schedules and activities remained constant.

Materials

Elements System

All participants experienced the full Elements program and training detailed in Chapter 4. During each session participants spent approximately 40 minutes performing the goal-based VEs with AF. Then, their feedback plots were reviewed, and finally the last 5-10 minutes were used for administering an exploratory VE. Briefly, the three exploratory VEs (Mixer, Squiggles, Swarm) departed from the stimulus response format of the goal-based tasks. Accordingly, these VEs encouraged participants to interact with the system freely (even creatively) and employ greater prospective control of their movements. The Squiggles and Swarm VEs also used multiple TUIs to afford bimanual movements during the tasks (see Chapter 4 for further details on the exploratory VEs and their administration). Participants experienced the first versions of each task in week 1, the second versions in week 2, versions 3 in week 3, and then selected which task and version to use during the 4th week of training.

Outcome Measures

The participants' upper-limb function was assessed using the three system-measured variables (accuracy, speed, efficiency), and the BBT (see Chapter 5 for details). Though minimal improvements were seen on the nuts-and-bolts MAND task in the case-studies, since the exploratory VEs were introduced in this investigation (and offered affordances for bimanual movements) this measure was used again. In addition to these tests the Neurobehavioral Functioning Inventory (NFI) was administered.

NFI. The NFI questionnaire contains 76 items with six sub-scales that assess general neurobehavioral symptoms and problems commonly encountered by patients with TBI (and other neurological disabilities). These include psychological and neuropsychological outcomes, daily living problems, general symptoms (e.g. fatigue), and functioning (Kreutzer, Steel, & Marwitz, 1999). The NFI sub-scales are Depression, Somatic, Memory/Attention, Communication, Aggression, and Motor. See Table 6.1 for example items from each. The

NFI was included presently to assess whether the Elements training had any effect beyond improving upper-limb function.

Table 6.1

Examples of NFI items by sub-scale.

Sub-scale	*Example items*: How often do you currently experience the following problems?
Depression	- Feel sad/blue
	- Feel hopeless
Somatic	- Stomach hurts
	- Trouble falling asleep
Memory/attention	- Forget yesterday's events
	- Easily distracted
Communication	- Difficulty pronouncing words
	- Trouble understanding conversation
Aggression	- Curse at others
	- Break or throw things
Motor	- Move slowly
	- Difficulty lifting heavy objects

Each item on the NFI is rated on a 5-point Likert scale (Never (1), Rarely (2), Sometimes (3), Often (4), Always (5)), based on frequency (Kreutzer, Marwitz, Seel, & Serio, 1996; Kreutzer, et al., 1999). Sub-scales are calculated by adding their respective scores (Depression 13 items; Somatic 11 items; Memory/Attention 19 items; Communication 10 items; Aggression 9 items; Motor 8 items (Kreutzer, et al., 1999)). The first 6 items are 'critical items' used to identify medical conditions, and are not counted in the total score. Hence, NFI scores range from 70 to 350, with higher scores indicating worse outcome.

The NFI has demonstrated good reliability and validity. Cronbach's alpha indicated high internal consistency within each sub-scale, with values between .86 and .95. Overall internal reliability was .97 (Kreutzer, et al., 1999). As expected, moderate overlap between the sub-scales has also been demonstrated. Correlations range from .44 to .67 (Kreutzer, et al., 1999). For example, somatic symptoms can be associated with depression (Kreutzer, et al., 1996).

The NFI has excellent face validity. The sub-scales were based on review of neurological disability research, existing measures, and interviewing patients and carers about common impairments. Construct validity has also been supported by factor analysis. The original 105 items were reduced to 76 after trials with 581 neurologically impaired participants and their carers (see (Kreutzer, et al., 1999) for demographic and diagnostic details). Thus, the NFI items were shown to accurately represent the constructs identified by the sub-scales, and overall neurobehavioral function.

Finally, a review of neurobehavioral assessments (Hall, Bushnik, Lakisic-Kazazic, Wright, & Cantagallo, 2001) found the NFI was superior to other scales. This study compared 10 outcome measures commonly used in TBI research including the Patient Competency Rating Scale, the FIM, and the Glasgow Outcome Scale (see (Hall, et al., 2001) for complete list of assessments). Forty-eight TBI patients were assessed on these scales, which were rated on ease of interpretation and sensitivity. The NFI had the best sensitivity (fewest ceiling effects) and was easiest to interpret due to its detailed norms. The NFI also correlated highly with the other scales (*r* values ranged from .81 to .83 (Hall, et al., 2001)), verifying its concurrent validity.

Procedure

Study Design

The within-groups design involved assessment of performance at three time points. Pre-test-1 (Pre1) and pre-test-2 (Pre2) were conducted four weeks apart before introduction of the VR. During this time participants underwent their normal rehabilitation. After Pre2 the four weeks of VR-training were conducted in conjunction with normal rehabilitation, followed by Post-test (Post) assessments. Figure 6.1 illustrates the research design

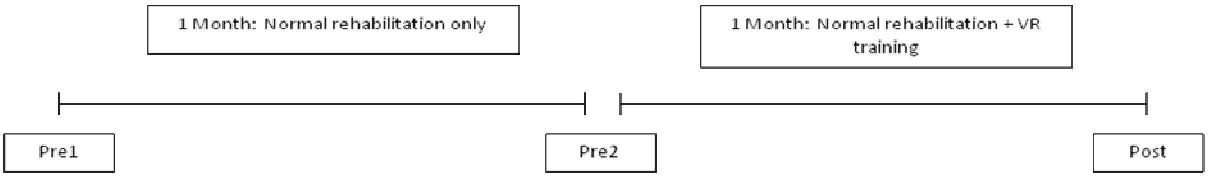


Figure 6.1. Diagram of the within-groups study design.

Data Analysis

Treatment effects. The primary analyses were comparing participants' performance on the six DVs (accuracy, speed, efficiency, BBT, MAND, NFI scores) between the pre-test and post-test periods. Traditionally, statistical comparison of three or more means involves Analysis of Variance (ANOVA), with follow up post-hoc tests. However, researchers in psychology (and other fields) have been criticised for incorrectly employing this exploratory method (Castaneda, Levin, & Dunham, 1993). It is argued that omnibus tests like ANOVA should not be used in intervention studies since it can be hypothesised that post-treatment performance will be higher than pre-treatment. Accordingly, a series of planned comparisons were conducted in this study (Castaneda, et al., 1993).

Planned comparisons are conceptually similar to performing a series of *t*-tests. However, they permit more thorough control of Type I error, and more complex comparisons can be conducted (see (Castaneda, et al., 1993; Howell, 2002) for review of the mathematical basis for planned comparisons). This method is considered an alternative to ANOVA, rather than an addendum. Indeed, research has demonstrated that planned comparisons are more statistically powerful than ANOVA (Howell, 2002). Planned comparisons are also resilient to violation of the ANOVA assumptions. This is important in within-groups studies where the assumption of sphericity is rarely tenable (Goodwin, 2005).

In the present study two planned comparisons were conducted for each DV. First, the Pre1 and Pre2 scores were compared and, second, Post scores were contrasted against Pre1 and Pre2 combined (these will be referred to as the Pre-test, and Treatment contrasts hereafter). We predicted larger effects for the Treatment contrasts compared with the Pre-test contrasts, indicating that the combined VR and conventional therapy would be more effective than conventional therapy alone.

As in the case-studies, the issue of clinical significance was relevant to this investigation. However, unlike N=1 research (where the JT method is used, and change on the DV is deemed 'functional' and 'reliable'), larger sample studies use effect sizes to gauge clinical significance (Ogles, et al., 2001). Therefore, effect sizes (partial η^2) were included for all planned comparisons. This procedure also helped temper the interpretation of significance tests where Type I errors are possible. These were interpreted as follows: .1 - .3 = 'small', .3 - . 5 = 'medium', and >.5 = 'large' (Cohen, 1992).

Results

Analysis of *Treatment Effects*

All descriptive statistics are presented in Table 6.2.

Table 6.2

Descriptive statistics for all DVs for Pre-test 1, Pre-test 2, and Post-test assessments.

Variable	Pre1 M(*SD*)	Pre2 M(*SD*)	Post M(*SD*)
Accuracy	Left: 46.26 (22.01)	51.32 (22.94)	64.25 (19.83)
(%)	Right: 56.86 (21.01)	59.16 (16.61)	73.62 (9.18)
Speed	L: 0.20 (0.08)	0.26 (0.09)	0.24 (0.06)
(m/s)	R: 0.23 (0.06)	0.28 (0.07)	0.31 (0.08)
Efficiency	L: 80.97 (20.25)	91.05 (5.23)	94.31 (4.77)
(%)	R: 92.61 (2.42)	93.54 (4.14)	97.68 (1.32)
BBT	L: 30.44 (19.59)	33 (17.49)	35.89 (15.83)
(no. blocks moved)	R: 46.66 (12.14)	47.33 (10.15)	53.33 (12.57)
MAND	Small: 26.19 (17.51)	22.01 (10.77)	21.62 (10.01)
(s)	Large: 33.74 (22.15)	26.79 (11.11)	25.08 (6.27)
NFI	128.67 (40.13)	128.56 (38.70)	112.89 (40.89)
(total score)			

Analysis of System-measured Performance

Accuracy. The Pre-test contrasts showed no significant change between the Pre1 and Pre2 assessments on either left, $F(1,8) = 1.64$, $p = .24$, partial $\eta^2 = .17$, or right hand, $F(1,8) = 0.43$, $p = .53$, partial $\eta^2 = .05$. However, the Treatment contrasts were significant for both left, $F(1,8) = 13.69$, $p = .01$, partial $\eta^2 = .63$, and right hand $F(1,8) = 9.45$, $p = .02$, partial $\eta^2 = .54$.

Speed. The Pre-test contrasts indicated significant improvement between participants' Pre1 and Pre2 scores for both their left, $F(1,8) = 12.82$, $p = .01$, partial $\eta^2 = .62$, and right hands $F(1,8) = 13.08$, $p = .01$, partial $\eta^2 = .62$. No significant change was found from the Treatment contrast for their left hand, $F(1,8) = 1.218$, $p = .30$, partial $\eta^2 = .13$. However, a significant change was found for their right, $F(1,8) = 11.5$, $p = .01$, partial $\eta^2 = .59$.

Efficiency. No significant change in efficiency was found from the Pre-test contrasts for participants' left, $F(1,8) = 2.55$, $p = .15$, partial $\eta^2 = .24$, or right hands, $F(1,8) = 0.37$, $p =$

.56, partial $\eta^2 = .04$. Additionally, while the Treatment contrast results for left hand approached significance, they did not pass the $\alpha = .05$ threshold, $F(1,8) = 4.78$, $p = .06$, partial $\eta^2 = .37$. The Treatment contrast indicated significant improvement for participants' right hands, $F(1,8) = 22.22$, $p = .002$, partial $\eta^2 = .74$.

Analysis of Standardised Measures

BBT. The Pre-test contrasts indicated no significant improvement in BBT scores for participants' left, $F(1,8) = 3.73$, $p = .09$, partial $\eta^2 = .32$, or right hands, $F(1,8) = 0.16$, $p = .70$, partial $\eta^2 = .02$. Significant improvement was noted from the Treatment contrasts for left, $F(1,8) = 5.68$, $p = .04$, partial $\eta^2 = .42$, and right hands, $F(1,8) = 12.61$, $p = .007$, partial $\eta^2 = .61$.

MAND. No significant improvement in the nuts-and-bolts task was found for either the large, $F(1,8) = 2.14$, $p = .18$, partial $\eta^2 = .21$, or small version $F(1,8) = 1.48$, $p = .26$, partial $\eta^2 = .16$ from the Pre-test contrasts. Similarly, the Treatment contrasts showed no significant improvements for either the large, $F(1,8) = 1.57$, $p = .246$, partial $\eta^2 = .16$, or small versions of the test, $F(1,8) = 0.90$, $p = .37$, partial $\eta^2 = .10$.

NFI. The Pre-test contrast indicated no significant improvement in NFI scores between Pre1 and Pre2, $F(1,8) = 0.11$, $p = .99$, partial $\eta^2 < .001$. A significant improvement was found from the Treatment contrast, $F(1,8) = 14.52$, $p = .005$, partial $\eta^2 = .65$.

Of the Pre-test contrasts, only the communication sub-scale of the NFI was significant, $F(1,8) = 5.57$, $p = .046$, partial $\eta^2 = .41$.Although each of the sub-scales showed a tendency to improve over the treatment period, only that for the memory/attention sub-scale was significant, $F(1,8) = 5.39$, $p = .049$, partial $\eta^2 = .403$. Table 6.3 contains the full planned comparison results for the NFI sub-scales. Figure 6.2 presents a summary of the partial η^2 effects for all DVs.

Table 6.3.

Planned comparison results for NFI sub-scales.

Sub-scale	Pte-test contrast	Treatment contrast
Depression	*F*(1,8) = 1.31, *p* = .29, partial η^2 = .14	*F*(1,8) = 2.72, *p* = .18, partial η^2 = .25
Somatic	*F*(1,8) = 0.11, *p* = .75, partial η^2 = .01	*F*(1,8) = 4.81, *p* = .06, partial η^2 = .38
Memory/Attention	*F*(1,8) = 2.21, *p* = .18, partial η^2 = .22	***F*(1,8) = 5.39, *p* = .049, partial η^2 = .403***
Aggression	*F*(1,8) = 0.90, *p* = .37, partial η^2 = .10	*F*(1,8) = 2.17, *p* = .18, partial η^2 = .21
Communication	***F*(1,8) = 5.57, *p* = .046, partial η^2 = .41***	*F*(1,8) = 1.90, *p* = .21, partial η^2 = .19
Motor	*F*(1,8) = 0.37, *p* = .56, partial η^2 = .04	*F*(1,8) = 2.45, *p* = .16, partial η^2 = .24

* - result significant at $\alpha = .05$

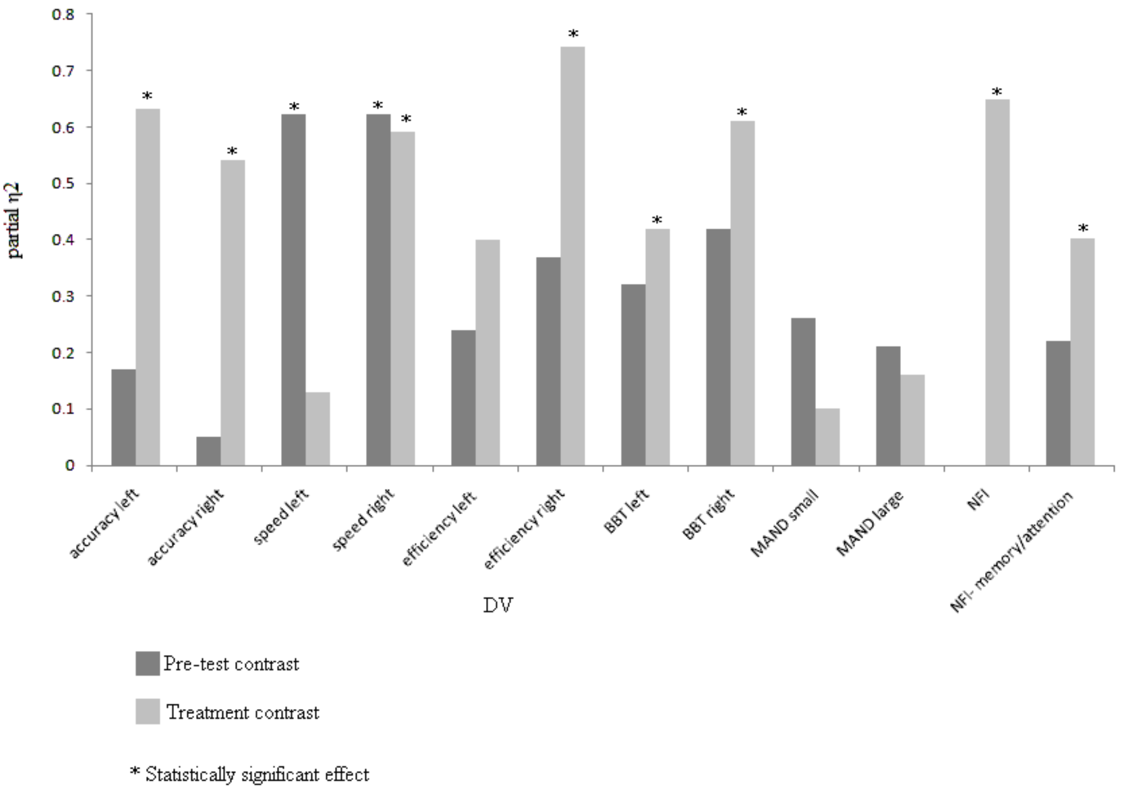


Figure 6.2. Partial η^2 results.

Discussion

The primary aim of this investigation was to further assess the efficacy of the Elements system using a within-groups design. First, the Pre-test contrasts revealed no significant improvement in performance on most measures from patients' traditional rehabilitation alone. Exceptions were seen on the speed variable for both hands. By comparison, Treatment contrasts (effects presented in Figure 6.2) supported the effectiveness of the system, across a range of measures. The patterns of performance on the system-rated and standardised assessments, limitations to the study, and future directions for research are discussed below.

System-measured Performance

Our participants' demonstrated significant improvements on movement accuracy based on the Treatment contrasts. In line with the case-study findings, the accuracy improvements were not at the detriment of movement speed. Accordingly, the large effect sizes recorded support the system's benefits to TBI patients' movement accuracy.

Significant improvements in movement speed, with strong effects, were found for both left and right hands from the two baseline assessments. Thus, these findings suggest traditional rehabilitation alone was effective at training movement speed over the 4-week period that separated Pre1 and Pre2. The VR-training was shown to improve speed further (based on the Treatment contrasts) for the right hand only. This pattern of results needs to be interpreted with reference to accuracy. The trade-off between speed and accuracy suggests fundamental changes in motor control for both hands. This theory indicates that speed or accuracy may be improved at the expense of the other variable (Shumway-Cook & Woollacott, 2007). In our study, for the right hand, significant improvements (with large effects) were noted for both speed and accuracy from the Treatment contrasts. For the left hand, significant improvement in accuracy (large effect) was paired with no significant change in speed. Since these results demonstrated no trade-off between speed and accuracy, they may indicate more genuine improvement in motor control.

As mentioned previously, this trade-off between speed and accuracy is central to Fitts' Law (see (Schmidt & Lee, 1999) for review, and (Fitts, 1954) for original research). Briefly, the Fitts' Law experiments demonstrate how movement time decreases as the task difficulty (e.g. accuracy required) increases (Schmidt & Lee, 1999). Furthermore, while this relationship has been shown across a variety of tasks and populations, minor variations in its presentation are noted between younger and older participants. Specifically, older participants demonstrate a greater trade-off between speed and accuracy (i.e. even a slight increase in required accuracy results in a dramatic loss in speed (Shumway-Cook & Woollacott, 2007)). Thus, as task complexity is increased older populations demonstrate poorer motor control, and functional performance. Since recovering TBI patients also experience difficulties in motor control as task complexity is increased (B. Wilson, 1998), an area for future research may be to formally examine this speed-accuracy relationship among recovering TBI patients using Fitts' algorithm. Formal assessment of this issue was beyond the scope of the present study.

The movement efficiency results also supported the Elements training. Both left and right demonstrated no change from normal rehabilitation alone (Pre-test contrast), followed by improvement after the VR-training (Treatment contrast) for the right hand. The left hand Treatment contrast just failed to reach significance, $p = .06$. The improvement in right hand performance is interesting in view of the fact that all participants scored highly on this variable during baseline assessment (generally over 90%). Thus, despite little room for improvement, significant results were still obtained for the right hand. This is an important finding since rehabilitation normally targets areas of limited function (Chua, et al., 2007; Nolan, 2005). Future interventions (both VR and non-VR) should target areas of high and minimal impairment to ascertain whether training effects in both are related to changes in functional skill.

Standardised Assessment Performance

The BBT results lend further support to the efficacy of the Elements system. Participants' general upper-limb function showed little change over the pre-test period, while significant improvements were recorded after VR-training (Treatment contrast). As discussed previously the BBT has excellent predictive validity (Herbet, et al., 1988; Platz, VanWijck, et al., 2005), and its scores are seen to accurately represent participants' functional abilities (Platz, Pinkowski, et al., 2005; Platz, VanWijck, et al., 2005). Accordingly, the medium to large effects from the BBT Treatment contrasts (taken as a representation of clinical significance) indicate that the Elements training likely benefited participants' daily function.

The MAND data indicated that bimanual coordination did not change significantly over one month of normal rehabilitation alone (Pre-test contrasts), or after the combination of normal and VR-therapy (Treatment contrasts). These results are in line with our earlier case-studies and other work showing minimal improvement on bimanual coordination following unilateral rehabilitation (Waller, et al., 2008). Since the majority of training was with the goal-based tasks which involved unilateral movement, these results are consistent with the task-specific benefits of training. However, previous research indicates that combining bimanual and unimanual training may lead to more generalised benefits (Waller, et al., 2008). Taken together, while the Squiggles and Swarm tasks do afford a degree of bimanual movement, this remains one aspect of training that may need to be increased in future trials.

The NFI was included in the present study to explore whether the Elements training can lead to associated benefits for our participants. Results demonstrated no significant change over the pre-test period, but fewer symptoms of dysfunction after the combined therapies. This pattern of results indicates benefits from the Elements training that extended beyond upper-limb function. It has been theorised that the enjoyment and novelty of VR may benefit participants beyond the movement parameters targeted, for instance by improving motivation and engagement in what is a novel and stimulating environment (M. Holden, 2005; Rizzo, et al., 2004). It is our belief that the combination of (real-time) AF and KR (the feedback plots) may have facilitated this effect. Further research is needed to isolate the particular aspects of VR-training responsible for these effects.

Treatment contrasts for the NFI scores indicated improvements across all sub-scales, with small to medium effects. However, only that for the memory/attention sub-scale was significant. This outcome might reflect the focus of our VR-training on motor planning using novel, interactive environments. In using the system and planning movements, patients are called upon to process a range of inputs (e.g., task instructions, layout of the workspace, and real-time feedback) in order to anticipate the outcomes of their action and achieve task goals (Shumway-Cook & Woollacott, 2007; Weigelt, Rosenbaum, Huelshorst, & Schack, 2009). These associated cognitive benefits are not trivial since memory and attention are commonly disrupted post TBI (Linden, et al., 2005). This effect could be explored further using standardised, objective tests of cognition.

Inclusion of the Exploratory VEs

In contrast to the case-study training, the present study included both the goal-based and exploratory VEs. We contend that the exploratory VEs helped promote motor control by placing different requirements on participants' motor planning than the goal-based tasks. By removing the 'goal' from the VEs, participants had to decide what movements to make, without guidance from the system. Based on the ITE model (Shumway-Cook & Woollacott, 2007), the exploratory VEs placed greater requirements on the individual by removing task constraints (the goal paradigm), and environmental prompts (cuing of movement locations).

Accordingly, participants may have experienced greater gains in motor function by experiencing both the goal-based and exploratory VEs.

Furthermore, it was apparent (through general observation and patient comments) that participants enjoyed using the exploratory VEs, and found them a positive change from normal rehabilitation. Concluding sessions with these tasks likely benefited the therapy by improving motivation for subsequent sessions, and overall enjoyment of the training. This contention is in line with previous studies (e.g. (M. Holden, et al., 1999; Jack, et al., 2001)), which viewed participants' enjoyment of VR-rehabilitation as a central factor in their motivation and motor learning.

Study Limitations

Despite the generally positive results from this study, some limitations must be considered. As discussed previously, the within-groups research design may be influenced by order effects (Goodwin, 2005). Though the present assessments took place a month apart, the possibility of order effects inflating our results cannot be ruled out. Follow-up research comparing treatment and control groups could be conducted to verify these findings. However, controlling for the type of traditional rehabilitation participants experienced would require a thorough matching process to ensure the study's internal validity. Furthermore, the sample-size used here may limit the generalisability of our findings. Thus, larger sample sizes are also a requirement of future studies.

Summary of Chapter 6

The findings presented here support those of our previous case-studies, demonstrating that the Elements VR-system can contribute to recovering upper-limb motor control in TBI. Our participants demonstrated no significant improvements in accuracy, efficiency, or BBT score from one month of normal rehabilitation alone, yet significant improvements were seen following VR and traditional therapy combined. Additionally, we noted improvements in participants' overall neurobehavioral functioning, especially memory and attention, following the VR-training (no improvements were evident from traditional therapy alone). These findings are significant in view of the fact that upper-limb training is often secondary to mobility training in rehabilitation centres. Moreover, the upper-limb training that does exist is often based on repetitive and labour-intensive treatments. For example, CIMT requires patients to immobilise their less affected hand, and perform daily living, or rehabilitation tasks with their affected hand for up to 6 hours per session (O'Sullivan & Schmitz, 2007;

Page & Levine, 2003). In contrast, the VR-based approach we have evaluated here uses a combination of standardised assessment, engaging and motivating workspaces, and both goal-directed and exploratory action.

It is noteworthy that training on the Elements system has seen more generalised improvement and specific gains in important areas of cognition (memory/attention) that support a range of behaviours. These promising findings suggest several areas of further research including investigation of the general benefits from VR-training and group comparisons based on the severity of TBI and time since injury. These potential areas of future research, along with the broader implications of the results presented here and in Chapter 5, are discussed in Chapter 7.

CHAPTER 7

GENERAL DISCUSSION

CHAPTER 7: GENERAL DISCUSSION

Overview of Chapter 7

The first section of the general discussion presents a summary of the systematic review, development of the Elements systems, and the evaluation studies 1 and 2. The findings of these studies are then compared to previous VR-rehabilitation research, and ecological motor control theory. Finally, implications of this thesis for clinical practice and future research are presented.

Summary of System Development and Investigations

The first stage in developing the Elements program was a systematic review of VR-rehabilitation literature. This review (Chapter 3) included 23 studies that assessed the clinical effects of upper-limb VR-training on stroke or TBI patients (Platz, et al., 1999)). The methodological quality of these studies was assessed using the DB rating scale, which scores papers on five sub-scales: Reporting, External validity, Bias, Internal validity/Confounding, and Power. The VR-systems in these studies applied either game-like or (virtual) teacher-animation designs. This review found 'moderate' support for both groups. These studies were fairly typical of developing research. They described well the nature of the therapy and participants, but had limited experimental control and low internal and external validity. Therefore, it was concluded that while these studies supported the efficacy of VR-rehabilitation, future research is yet required.

The Elements program was based on an ecological approach to motor behaviour--the ITE model. Here movement is seen to result from an interaction between individual, task, and environmental factors (described in Chapter 4). Thus, we used VR to vary aspects of the rehabilitation tasks and environments according to the individual's capacity to engage, respond and re-learn basic motor patterns and skills. Our system offered both goal-based and exploratory forms of interaction. The four goal-based VEs shared a stimulus-response format, requiring participants to move the object to cued locations on the LCD display. These tasks placed progressively greater demands on motor planning by varying task constraints like distance. AF was provided in real-time to promote multimodal integration and knowledge of movement outcomes. In the three exploratory VEs there was no explicit task goal, or movement cuing. This encouraged user-driven interaction.

The Elements program also has an assessment function. Participants' movement accuracy, speed, and efficiency were measured during the goal-based tasks. Feedback plots from this data allowed participants to monitor their performance, and goal achievement. The Elements training consisted of 12 one-hour sessions conducted over four weeks.

For the first evaluation of the system (Study 1, presented in Chapter 5), single-participant case-studies were conducted, using an ABA design with multiple-baselines. The participants were three males with extremely severe TBI (TJ aged 21, and SK and AN both aged 20). Upper-limb function was assessed using the system-measured variables, the BBT, and two tasks from MAND that test bimanual coordination (the nuts-and-bolts, and bead threading tasks). Performance trends were assessed using visual analysis of smoothed data (based on exponential data smoothing) and statistical analyses (2*SD* band, or SMTA). Improved movement accuracy was noted for all participants (significant for TJ and AN), and this was maintained into the second baseline phase. No improvements in movement speed were evident, and all participants improved movement efficiency for their right hand (with TJ showing improvement on both hands). All BBT scores improved following VR-training (significant for TJ and AN on their left, and SK on his right). On the MAND, mild improvements were seen on the nuts-and-bolts task, though these were not statistically significant. Finally, both TJ and SK improved significantly on the bead threading task. These generally positive results supported the efficacy of the Elements VR-training, and justified a more rigorous evaluation.

Study 2 (Chapter 6) was a within-groups investigation, which included nine very severe/extremely severe TBI patients. The aim of this study was to continue trialling the Elements system with a larger sample population. The same assessments were used here as in Study 1 (minus the bead threading task), with the addition of a measure of neurobehavioral function (the NFI). Assessments took place on three occasions. Pre-test 1 and 2 (Pre1 and Pre2) were 1 month apart. During this time participants continued their normal therapies. Four weeks of VR-training were then conducted (concurrent with normal rehabilitation), followed by post-test (Post) assessments. The performance data were analysed using two planned contrasts per DV. These contrasted Pre1 and Pre2 (the Pre-test contrast), then Pre1 and Pre2 combined against Post scores (the Treatment contrast). All Pre-test contrasts were not significant with the exception of movement speed (both left and right hand). Significant Treatment contrasts were found for movement accuracy (left and right), speed (right only), efficiency (right only), BBT (both hands), total NFI score, and the memory/attention NFI sub-scale. Taken together, the findings of Study 2 also supported the Elements system, demonstrating its benefits for acquisition of upper-limb and neurobehavioral function.

In sum, these initial evaluations of the Elements program generated positive results, which support the application of the system. However, these studies should be considered preliminary, due to their sample sizes, and methodologies. Accordingly, the next stage of this research will be to continue trialling the Elements program utilising multiple group designs.

Implications for VR-rehabilitation

Comparison of Current and Previous Research

As discussed in Chapter 3, the efficacy of upper-limb VR-rehabilitation has been previously investigated, almost exclusively among stroke patients. Accordingly, comparison of our findings to these studies is warranted to assess the consistency of our results, and their support for VR-rehabilitation generally.

Game-like Systems

Elements would be classified as a game-like system, since it required participants to interact with engaging/fun VEs, and did not include a teacher-animation. Congruent to our investigations, most previous research has found positive results. However, comparison with key studies' in this group demonstrates that while our results are in line with previous findings, they may provide stronger support for VR-rehabilitation.

As in the current work, the Rutgers group utilised a combination of case-studies (Boian, et al., 2002; Jack, et al., 2001) and within-groups research (Adamovich, et al., 2004). Their program differed from Elements by targeting finger speed, fractionation, and ROM (automatically measured by their VR-system), rather than general upper-limb function. Figure 7.1 illustrates the four VEs used in the Rutgers system. Despite the similarity in research design between these investigations and ours, methodological differences remain. Their initial case-studies did not utilise standard time-sequence methodology, or statistical analyses (Boian, et al., 2002; Jack, et al., 2001). Rather, they reported percentage change on the system-measured variables and JTAF between single pre- and post-test assessments. Thus, the support for their system (and VR-rehabilitation generally) is reduced, since treatment effects cannot be separated from other factors (e.g. fatigue during baseline testing) from single assessments (Backman & Harris, 1999). Further, this group's within-subjects study (Adamovich, et al., 2004) yielded more varied results than ours, despite more intense VR-training (approximately 26 hrs in total, compared to our 12 hrs). Significant improvements were seen for six of their eight stroke participants in ROM, seven in finger fractionation, four in speed, and three in strength, between pre and post-test assessments.

However, significant improvements were seen on the JTAF for participants' more affected hand only (Adamovich, et al., 2004). Conversely, our within-groups participants improved significantly for both hands on the BBT. This could indicate that VR-rehabilitation is more beneficial for patients recovering from TBI than stroke. Exploring this possibility may be a subject for future research.

Results from the Rutgers studies and ours both indicate improvements from VR-rehabilitation, and support the game-like approach. The present results are particularly encouraging since more rigorous methodologies were applied, and resulted in more improvements. This conclusion may also apply for other studies. For example, some did not apply adequate control procedures (Broeren, et al., 2004; Fischer, et al., 2007), or appropriate statistical analyses (Broeren, et al., 2008; Stewart, et al., 2007; Yeh, et al., 2007).

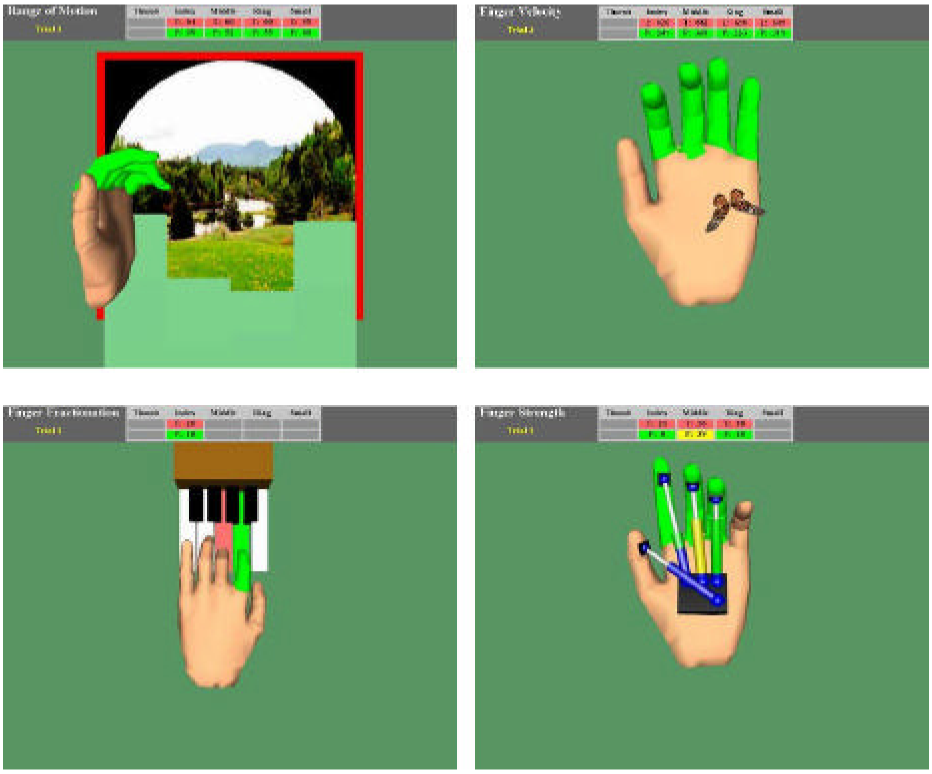


Figure 7.1. Screenshots of the Rutgers VR-system (Boian, et al., 2002).

Teacher-animation Studies

Provision of AF using teacher-animations was the premise of the majority of the studies in this group (e.g. the Piron investigations). Though the Elements system did not include a teacher-animation, our philosophy of providing AF during VR-training was congruent to these investigations.

The sequence of Holden et al.'s studies was similar to the present research. Their initial investigations (M. Holden, Dettwiler, et al., 2001; M. Holden, Dyar, et al., 2001; M. Holden, et al., 1999) utilised case-study designs. Here stroke patients viewed a teacher-animation demonstrating reaching tasks (mailing a letter, or pouring a jug of water), which they copied using objects with tracking sensors. In this original version participants saw a virtual representation the object moving in space. During these tasks, they received AF on their performance (the teacher-animation's trajectory and the participant's were displayed simultaneously to highlight discrepancies). The primary methodological difference between the present case-studies and these is the number of assessments per phase. Though reach trajectory (assessed by their system) and scores on standardised measures (FMA, WMT, SAILS) were improved in the Holden studies, only single assessments were conducted pre- and post-training. In one paper (M. Holden, Dettwiler, et al., 2001) the authors indentified their design as a time-sequence method (specifically an AABABAA design). However, again, only single assessments were taken per phase, obscuring the effect of the treatment. Further, these studies did not utilise statistical analyses, and only provided percentage improvements. Accordingly, these results provide only moderate support for the system's efficacy.

Larger sample studies were also conducted by Holden and Dyar (2002) and Holden et al. (2007). These used a modified VR-program, where participants copied an arm animation's reaching motion, rather than an object transport task (see Figure 7.2). The authors did not explain their system revision. However, others have theorised that an arm animation allows participants to more accurately map their movements to those of the teacher (Gaggioli, et al., 2007). It is plausible that this reasoning was also the basis for Holden and colleagues' revised system. The 2002 Holden study utilised paired-sample *t*-tests to compare performance on the FMA and WMT between pre- and post-test. Significant improvements were found. Most recently (M. Holden, et al., 2007) this group used ANOVAs to compare the mean of two pre-tests, against three post-test assessments (after 15, then 30 VR-sessions, and at four month follow-up) among 11 stroke patients. Post-hoc comparisons showed significant improvements at each assessment. Though less statistically powerful than the planned comparisons used in the present within-groups study (Howell, 2002), these results still provide good support for their system, and the use of AF in VR-rehabilitation generally.

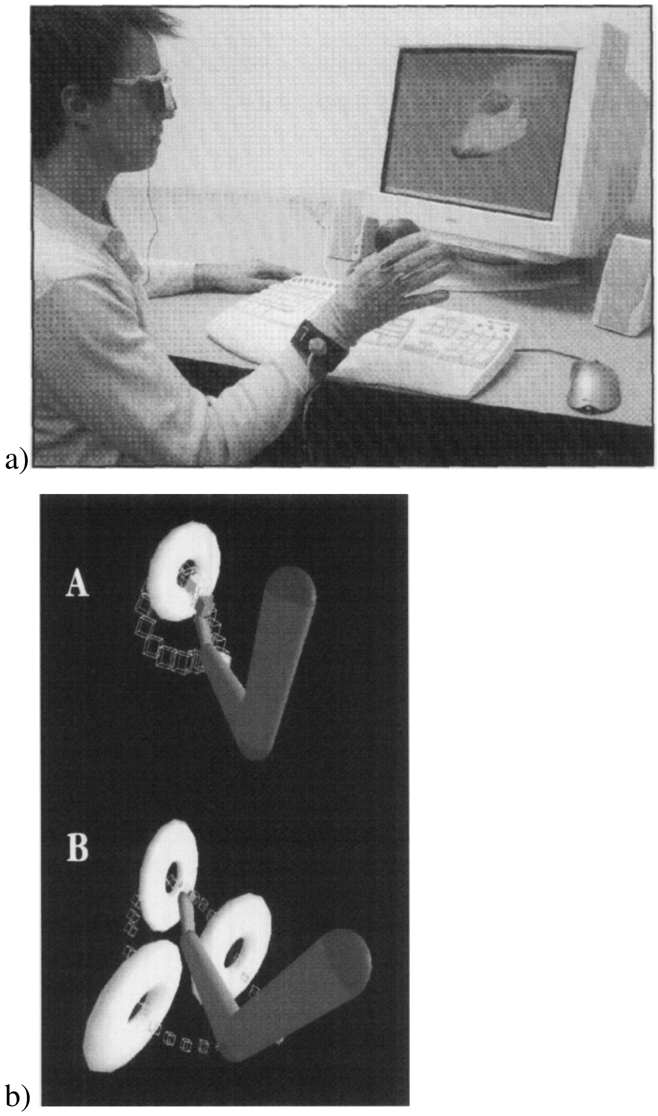


Figure 7.2. The Holden group's VR-system. a) System setup; b) sample VEs (M. Holden & Dyar, 2002).

Similar to the original Holden program, the Piron group's VR-system (Piron, et al., 2007; Piron, et al., 2005; Piron, et al., 2004; Piron, et al., 2003) required participants to copy movements of a teacher-animation using objects with tracking sensors (see Figure 7.3). Here too AF was provided by displaying participants' movement trajectory alongside the teacher's. However, this system was trialled using larger sample sizes than the Holden group, and the present studies (Piron, et al., 2007; Piron, et al., 2005; Piron, et al., 2003). Two of these investigations utilised within-groups designs. These required 24 (Piron, et al., 2003), and 50 (Piron, et al., 2005), stroke patients to undergo 4-7 weeks of VR-training, with five one-hour sessions per week. Participants' pre- and post-test scores on standardised assessments (the

FMA and FIM) were compared using Wilcoxon and Mann-Whitney U tests. In line with our findings their participants demonstrated significant improvements. These results were followed-up with a between-groups study, contrasting groups who underwent only VR-therapy or traditional therapy (19 participants in each) (Piron, et al., 2007). However, this study's methodology was limited. The design did not control for natural recovery by conducting baseline assessments or including a no-treatment control group. In our studies we opted for baseline assessment periods to gauge natural recovery. Further, there was no significant difference between the groups' performance pre- to post-test (Piron, et al., 2007). Thus, these inconsistent results do not support the use of VR-rehabilitation alone (and are limited by the study's design). Our findings suggest that a combination of traditional and VR-rehabilitation may be effective for applying this technology. However, further research is needed to assess this conclusion.

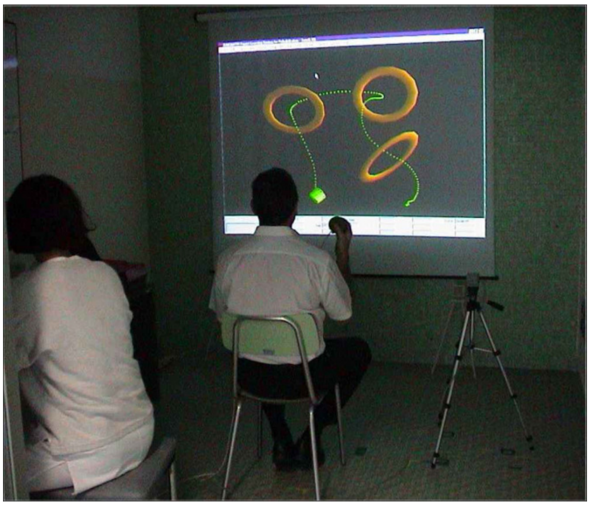


Figure 7.3. Photo of the Piron group's VR-rehabilitation system (Piron, et al., 2007).

Accordingly, the similarity in methodology and outcome of the Holden and earlier Piron studies (excepting the inconsistent findings from their 2007 paper), and the present investigations further supports the use of AF in VR-rehabilitation. Indeed, while these previous studies support teacher-animation AF, our findings suggest that AF as part of the action environment may also be an effective method. Future VR-systems may explore the possibility of including both forms AF.

VR Components and Rehabilitation Outcomes

As mentioned in Chapter 2, the term VR encompasses a wide range of technology in rehabilitation (Cobb & Sharkey, 2007). However, no studies have compared the efficacy of the varying components of VR. It is possible that different system components may impact performance in different ways. For example, in the Rutgers studies, and the Stewart et al. (2007) system, attaching the interface device to the participant's hand may have restricted their movement, and reduced improvement in arm function. HMD displays, or 3D glasses, may also be restricting/distracting for participants (e.g. (Broeren, et al., 2008; Fischer, et al., 2007)). Further, different patients may benefit more from one type of technology or form of interaction over another. Indeed, the ability to tailor the rehabilitation environment to suit the needs of the patient is one of the strengths of VR-rehabilitation.

While these ideas remain speculative at present, the possibility remains that the type of technology used in VR-rehabilitation may impact upon its outcomes. Accordingly, investigation of which components of VR-systems are most conducive to improvements in motor control remains an area for future research.

Summary

The current findings of improved upper-limb function following VR-rehabilitation match those from previous game-like and teacher-animation studies. However, it may be argued that our investigations were based on more rigorous designs. For example, previous case-studies (e.g. (Boian, et al., 2002; M. Holden, Dyar, et al., 2001)) utilised single assessments per phase, and no statistical analysis. Furthermore, these studies were conducted only among stroke patients. The present findings indicate that VR-rehabilitation may also be effective among TBI patients.

It should be acknowledged that our studies were based on quasi-experimental designs (as were the majority of previous investigations discussed). Since practice effects were not fully controlled, causality between the treatment and outcomes cannot be claimed (Howell, 2002). Thus, further true-experimental research is required. However, when investigating new technology successful small-sample studies are often a prerequisite for larger-scale investigations (Jackson, 2006). Therefore, in the context of ongoing research the present results (and those of previous research) provide good initial support for the use of VR, and justification for conducting larger true-experimental studies.

Qualitative Evaluation of the Elements Design and Administration

The following qualitative discussion on aspects of the Elements system's design and administration (based on observations and participant comments) is intended to suggest avenues for further research and design, rather than provide a formal evaluation.

System Design

Use of Game-like Interaction with AF

The majority of participants commented that the Elements system was fun and extremely different to their normal therapy. Thus, we contend that enjoyment was a central factor in the training. This observation is in line with previous studies (e.g. (Gaggioli, et al., 2006; Jack, et al., 2001)). However, the novelty of using VR seemed to diminish over the course of the training. One participant commented (after six sessions) that it became part of his 'normal routine'. Thus, while VR's novelty may have interested participants initially, it was likely the provision of movement feedback that maintained their motivation. Accordingly, 'just having fun' may not be a sustainable basis for VR-rehabilitation. Rather, VR-systems need an active therapeutic component to engage participants after the initial novelty has dissipated.

Use of TUIs

One of the key design choices in Elements was the use of TUIs as the interface device. The basic circle, rectangle, triangle, and pentagon shapes were selected to maximise the grasp, lift, place affordances in the VEs. Participants commented that they liked the size and shapes of the objects, and found them 'easy to move around'. Two participants said they liked moving these objects because it reminded them of an OT task (moving cups on a table), but was more fun. Accordingly, we contend that the inclusion of TUIs was a successful design choice.

Assessment and Provision of Feedback Plots

In addition to rehabilitation, the Elements system had an assessment function (monitoring accuracy, speed, and efficiency). A central part of the assessment was the provision of feedback plots. Several participants said that monitoring their performance in this way was the best aspects of the training, and was very different to normal therapy. Further, tracking their performance on the feedback plots typically became a focus for the participants' experience. They frequently commented on their performance during the goal-based tasks (e.g. ‘I don’t think I’m going as fast as yesterday’). Three participants even requested copies of their feedback plots to take home, and show their improvements to their families. Thus, the assessment function (in particular the feedback plots) was successful, and important to the participants’ training.

System Usability

As discussed in Chapter 2, VR-rehabilitation systems have received mixed usability reports. Generally patients find VR easy to use, and enjoyable (e.g. (Adamovich, et al., 2004; Christiansen, et al., 1998)). However, clinicians do not (e.g. (Edmans, et al., 2004; Pierce, et al., 2001)). In the Elements studies our participants reported enjoying the system, and that it was easy to use. Further, Elements was built using off-the-shelf PC hardware, and its OI was designed to be intuitive and easy to use. The initial system setup, which required entering participants into the database and calibrating the camera, took less than 10 minutes. The daily set-up (loading users, selecting tasks and AF) took less than 5 minute. The data output by the system was also easy to manipulate, and was quickly cut and pasted into Excel spreadsheets to create feedback plots (this was done in a matter of seconds each session). Additionally, none of our users experienced instances of cyber-sickness. Thus we believe that the Elements system demonstrated good patient and clinician usability. However, further, quantitative analysis is required to verify this conclusion.

Administration Protocol

Person-centered Administration

An important aspect of the Elements training was how the sessions were conducted. We adopted a person-centered administration approach, which emphasises that the attitudes of the therapist and their relationship with the patient are central in promoting recovery (see (Elliotta & Freire, 2007; Raskin, 2004) for review). Thus, during the Elements training establishing a friendly relationship/rapport with the participants was essential to keep the mood of the training light. And, we contend (based observation of participants, and reports from their families) that the person-centered administration benefited the training by making the sessions more personable and enjoyable.

Goal Setting

One aspect of the Elements training that was less effective than anticipated was the goal setting. It was theorised that goal setting would improve patients’ motivation, and outcomes from training (Dixon, et al., 2007). However, our participants seemed indifferent to their goals and whether they met them. Rather, participants preferred to simply track their performance on the feedback plots.

Goal setting guidelines in rehabilitation often employ the SMART acronym. Meaning goals should be Specific, Measurable, Achievable, Relevant, and Time-limited (Siegert & Taylor, 2004). In the present studies, our participants' were to attain set scores for the three system-measured variables, satisfying the specific and measurable criteria. Further, their goals were to be achieved each week, and were based on their previous performance, thus meeting the achievable and time-limited criteria. Though we believed that attaining set scores on the system-measured variables would be relevant for our participants (since most would be young males, experienced with video-game technology and concepts, such as attaining scores for a VR-game (Ellis, 1994)), their disinterest in the goals indicates that the 'relevant' criterion may not have been met. But, since the feedback plots were still extremely helpful, it is unlikely that this affected the results. The relevance of goal setting would, however, need to be enhanced in future studies. For example, by setting goals based on ADL assessments.

Summary

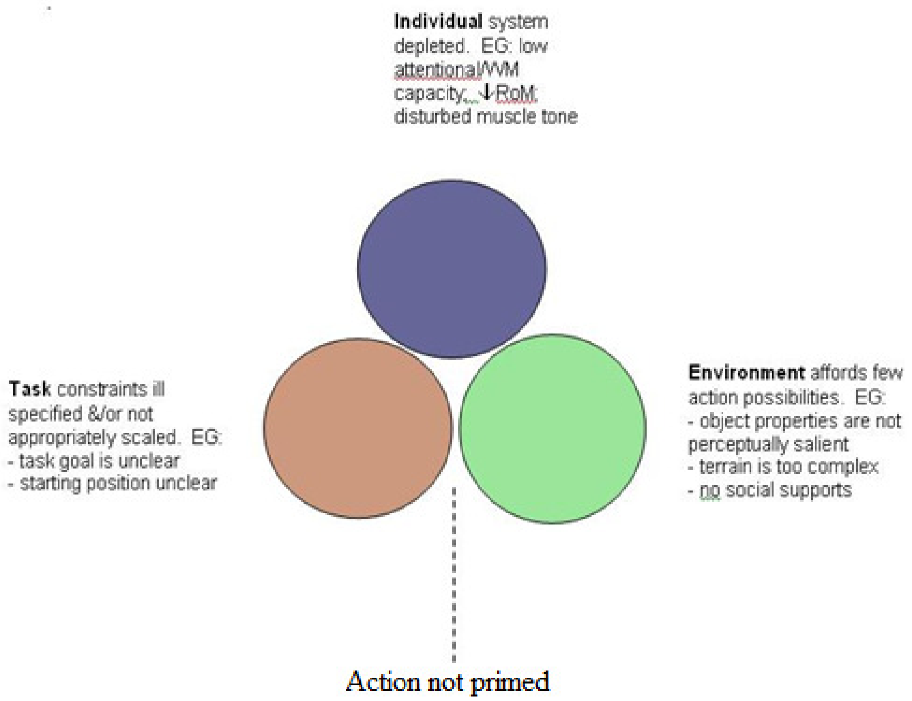
In summary, based on qualitative evaluation, our application of game-like interactions with AF, the inclusion of TUIs, and provision of feedback plots were effective design choices. Additionally, applying a person-centered administration approach was also beneficial. However, revision of the goal-setting procedure would be required in future studies.

Theoretical and Neurological Implications of Results

The Elements System and the ITE Model

The Elements system was based on an ecological model of motor control, the ITE model. Ecological theory states that functional movement arises from an individual interacting effectively with their environment, based on the actions it affords (Shumway-Cook & Woollacott, 2007). The ITE model extends this perspective, proposing that movement results from a balanced interaction between the *individual*, the *task* being performed and the action *environment* (Law, 1996; Law, et al., 1994; Newell & Jordan, 2008; Shumway-Cook & Woollacott, 2007; Wilson, et al., 2006)Wilson, et al., 2006. Elements aimed to promote functional movement by providing (virtual) tasks and environments that factor in TBI patients' individual impairments, and promote functional movement. For example, the task difficulty was scaled to meet participants' perceptual limitations, and reduced speed of mental processing. We also provided them with AF in the action environment to account for impaired movement feedback processing. Figure 7.4 illustrates this process.

1. Learning context unsupported - minimal ITE overlap



2. Learning context supported - increased ITE overlap

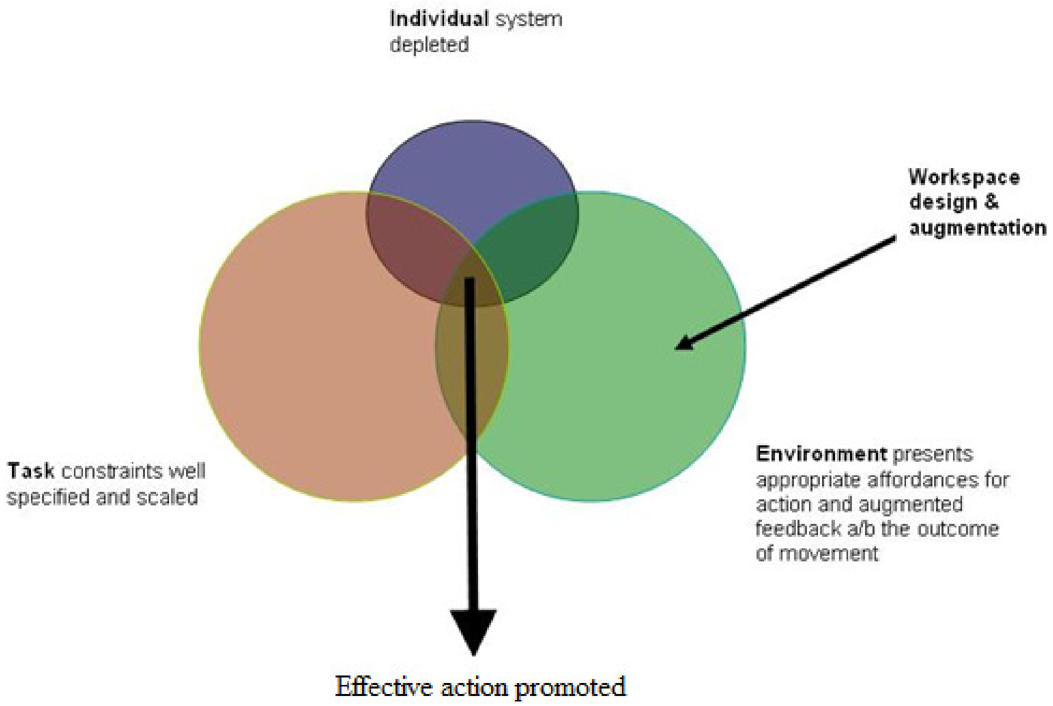


Figure 7.4. Promoting functional movement using the Elements system.

Thus, we contend that participating in an ITE system that encouraged functional movements improved participants' rate of motor learning. Further, a central tenant of the ITE model is the reciprocal nature of the interaction between the three factors (Law, 1996). Therefore, participants' improvements in motor control likely fed back into the system during training. This would allow them to better interact with the task and environmental factors, and promote greater functional benefits.

Additionally, despite our system's focus on upper-limb abilities, the training also benefited general neurobehavioral function (based on the NFI results). Possible improvements in participants' self-efficacy as their role in the ITE interaction became more effective may explain this effect. Indeed, ecological theory states that wellbeing and self-efficacy are linked to perceived capability in our environment (Shumway-Cook & Woollacott, 2007). However, whether neurobehavioral benefits result from improved self-efficacy in this manner is an area for future study.

An Ecological View of TBI and Rehabilitation

The present findings indicate that TBI patients' impairments and rehabilitation may be understood by adopting an ITE perspective. Specifically, by acknowledging that individual factors are just one aspect of motor impairment, open to change through manipulation of task and environmental aspects. Thus, TBI patients' disabilities may reflect task and environmental factors impeding their performance. The ITE model emphasises optimising both task and environment in redeveloping functional movements among TBI patients. Although this perspective has been put forward previously (Law, 1996), our findings support its application, and justify further research.

Summary

To summarise, the Elements system drew on the ITE model of motor-movement in its design. Our results lend support to the application of this model. We theorise that participants may have experienced more rapid development of motor control by engaging in functional movement, facilitated by our VR-training. Accordingly, TBI rehabilitation generally may benefit from applying the ITE model in understanding patients' impairments, and recovery. Nonetheless, the mechanics underlying our participants' improved performance remains a point for discussion. As outlined below, one possible explanation is that the VR-training resulted in changes at a neurological level.

Neural Plasticity: Possible Mechanisms for Functional Change

Research has demonstrated that areas of the brain (for example, the cortex) can have their structure, and function, altered through stimulation and active use (Bach-Y-Rita, 2003; Jones, Hawrylak, Klintsova, & Greenough, 1998). This process is termed neural plasticity (NP), and plays a central role in the reacquisition of motor skills following TBI (Jones, et al., 1998; Ward, 2005). NP post-TBI progresses through three stages (Wieloch & Nikolich, 2006). The first involves removing dead tissue, repairing damaged cells, and recovery of neuronal function. Stage two is characterised by axonal growth, (neuron) spine remodelling, and activation. The final stage involves establishing and consolidating neural pathways (Wieloch & Nikolich, 2006). These stages are described below, and provide a context for how VR-training may promote NP among TBI patients.

Stages of NP Post-TBI

Stage 1. The first stage in post-TBI NP occurs during the initial days following the accident (estimated one to four weeks depending on severity (Wieloch & Nikolich, 2006)). During this time dead neurons are removed, while surviving ones are repaired, and resume their normal function. Initially, the GABAergic system is down regulated, creating an optimal environment for further NP. Brain sectors surrounding damaged areas also produce proteins and hormones during this stage that enhance synaptogenesis and axonal sprouting (see (Wieloch & Nikolich, 2006) for details). Furthermore, research has indicated that mental stimulation during this stage may promote NP (Jones, et al., 1998).

Stage 2. Stage 2 occurs after the brain has been primed for longer lasting NP during stage 1. This stage is characterised by functional cell plasticity due to axonal sprouting in regions neighbouring damaged brain sectors. Here undamaged axons develop new synaptic connections (through axonal growth, dendritic arborisation, and spine remodelling, see (Wieloch & Nikolich, 2006) for discussion), to reconnect damaged neural pathways. Angiogenesis (increased vascularisation of damaged brain centres), and growth factors that enhance myelination (released from glial cells) are also active during this time (Busch, Buschmann, Mies, Bode, & hossman, 2003; Rickhag, et al., 2006). Once again, mental activity/stimulation can advance these processes (Matsumori, et al., 2006).

Stage 3. Stage 3 involves consolidation of previous stages' NP, and begins up to 6 months post TBI. This stage marks the beginning of 'normal' NP (Wieloch & Nikolich, 2006), and involves strengthening neural pathways through stimulation (i.e. long-term potentiation) (Martinez & Derrick, 1996). For example, repeated activation can make receptors on the post-synaptic neurons more sensitive, requiring less stimulation to induce an action potential. The number of receptor sites on the post-synaptic neuron may also be increased. New synaptic connections may be produced (synaptogenesis) when pre-synaptic axon terminals divide to produce new terminals (see (Garner, Zhai, Gundelfinger, & Ziv, 2002) and (Waites, Craig, & Garner, 2005) for discussion). Additional mechanisms aid in consolidating NP during this stage. The primary one being neurogenesis.

Neurogenesis is the development of new neurons, and is central to recovery post-TBI (McMillan, Robertson, & Wilson, 1999). Briefly, people possess neural proginator cells (similar to stem cells), which lie dormant in various brain sectors, such as the hippocampus. Although these cells normally replace neurons that die every day, following TBI they are proliferated to damaged areas of the brain to aid recovery (see (Wiltrout, Lang, Yan, Dempsey, & Vemuganti, 2007) for discussion on this process). There they are slowly integrated into existing (and newly forming) neural pathways (Eriksson, 2003). Additionally, research has demonstrated that enriched environment training can further neurogenesis in TBI recovery (Wieloch & Nikolich, 2006).

VR and NP

A common finding in post-TBI NP research is that mental stimulation hastens the processes at each stage (Jones, et al., 1998; Matsumori, et al., 2006; Wieloch & Nikolich, 2006). Accordingly, our findings may have resulted from VR facilitating NP (specifically stage 3 processes, based on the TSI of our participants) in brain regions responsible for motor control. For example, in the primary motor cortex, which is the region most active during motor planning and action (Ogawa, Inui, & Sugio, 2006). NP may also have occurred in the premotor cortex, and supplementary motor area, which contribute to motor control (Frost, Barbay, Friel, Plautz, & Nudo, 2003). This contention is supported by evidence that repeated stimulation of these areas results in NP, and improved motor function (Martinez & Derrick, 1996; Stephen, Szaflarski., Eliassen, Pan, & Cramer, 2009). Furthermore, our NFI findings indicate that memory and attention improved from VR-training. Thus, NP may also have occurred in brain regions associated with these functions (the hippocampus and posterior parietal cortex (Giovanello, Schnyer, & Verfaellie, 2004; Hu, Bu, Song, Zhen, & Liu, 2009)).

Currently only one investigation has assessed neurological changes following VR-rehabilitation (results reported in (Jang, et al., 2005; You, et al., 2005), see Table 3.3 for details). These participants demonstrated significantly increased activity in the primary motor cortex (based on fMRI imaging) following VR-training. Although these findings were from stroke patients, they support our contention that VR may improve motor function by facilitating NP.

Clinical Implication of Results

Efficacy and Integration of VR-rehabilitation

Two issues to consider in VR-rehabilitation are its efficacy, and potential for integration with normal therapy (M. Holden, 2005). Though based on case-study and within-groups designs, our results indicate that VR-training can contribute to improvements in motor control. Additionally, these studies were conducted in a major rehabilitation facility, with TBI patients undergoing normal therapy. Therefore our results both support the efficacy of VR-rehabilitation and its potential for integration with traditional methods.

VR for Assessment

In addition to therapy, the Elements system was utilised as an assessment tool. This function performed well, and provided accuracy, speed, and efficiency data for both investigations. Therefore, we contend that VR may be a viable assessment tool in future TBI rehabilitation. Moreover, the extremely popular feedback plots were based on these assessments. Although provision of numeric KR feedback is recommended in rehabilitation (VanVliet & Wulf, 2006), it was not included in our participants' traditional therapy. Indeed, the success of our feedback plots suggests wider use of this method may be investigated in the future.

Who Will Benefit from VR-training

Research has indicated that longer TSI and greater injury severity predict worse outcomes from rehabilitation (Bajo & Fleminger, 2002; B. Wilson, 1998). However, our results indicate that severe/extremely severe and long TSI participants may demonstrate improvements through VR-rehabilitation. Indeed, these results suggest that additional research investigating the benefits of traditional rehabilitation among severe and long TSI patients may be required.

Limitations and Implications for Future Research

Limitations

System Design

Though the BBT results indicated benefits to participants' general upper-limb function, the Elements system's design may need to be modified to increase generalisation in the future. For example, the current tasks only required movement on a single, horizontal plane. Conversely, many ADLs require multi-planar movements (e.g. moving a cup from a shelf to a table (Hopkins & Smith, 1993)). Designing VEs that afford movements on multiple planes may be an area of interest for future developers. For example, systems may require participants to reach and touch targets viewed on a vertical display, and interact with TUIs on a horizontal plane. Additionally, while the exploratory VEs incorporated multiple objects (encouraging bimanual movements), additional goal-based VEs may be developed that set up affordances for bimanual coordination (D. Rose & Winstein, 2004; Winstein, et al., 2003). Based on the MAND results the current training had minimal impact on bimanual abilities.

Adherence to Training Protocol

One limitation commonly encountered in rehabilitation studies is imperfect adherence to administration protocol. In our studies we encountered difficulties with participants rescheduling sessions, arriving late, or having to schedule their sessions early in the morning, or immediately after other strenuous therapy (e.g. physiotherapy or hydrotherapy). These factors may have reduced the magnitude of some participants' improvements. However, this may add to the generalisability of our findings, as these issues are common in traditional rehabilitation.

Volunteer Participants

Additionally, all of our participants were volunteers. Thus, they may represent a more motivated part of the TBI population. Future research may find treatment effects are reduced if VR-training is mandatory.

Directions for Future Research

True-experimental Design Studies

As mentioned previously, our trials were quasi-experimental in their design. Thus, the next phase would be conducting true-experimental studies. For example, assessing pre- and post-test performance of four randomly allocated groups (no-treatment, VR-only, traditional only, VR and traditional therapy) would demonstrate the individual and combined effects of VR-rehabilitation. However, this design would need a very large sample. Further, cognitive and functional abilities, and type of traditional therapy used would need to be controlled. Conducting research of this magnitude would only be feasible with support from previous small sample studies (such as those presented here).

Investigation of TBI Severity and TSI

Previous research has demonstrated that more severe TBI is associated with reduced recovery in ADL function (Hoofien, Vakil, Gilboa, Donovick, & Barak, 2002; Toschlog, et al., 2003), cognitive abilities (e.g. attention, memory, and executive function (Ponsford, Draper, & Schönberger, 2008)), and upper-limb movement (Katz, Alexander, & Klein, 1998) following rehabilitation. However, research into long-term outcomes for TBI patients has delivered mixed findings (Andelic, et al., 2008; Dikmen, Machamer, Powell, & Temkin, 2003; Draper & Ponsford, 2008; Olver, Ponsford, & Curran, 1996). While impairments in social and emotional functioning, and participation in school/work are common up to 10 years post TBI, (Albensi & Janigro, 2003; Olver, et al., 1996) some patients (up to 30%) improve (even back to normal levels) in areas of executive function, attention, speed of mental processing (Dikmen, et al., 2003; Draper & Ponsford, 2008), and ADL performance (Dikmen, et al., 2003; Olver, et al., 1996). It is possible that improved speed of mental processing and executive function in patients with longer TSI may permit better processing of task instructions and use of AF. However, this question could not be assessed in the present studies, based on their sample size. Thus, it remains to be investigated in larger sample trials.

Additionally, it is not entirely clear whether training on a system based mainly on unilateral movements will transfer well to bimanual action. Eastridge and Mozzoni (2005) provide some data that show that improvements in bimanual coordination are achievable following unilateral training. Future work needs to investigate this transfer issue.

Identification of Active Components of VR-training

The present studies aimed to trial the Elements system as a complete treatment package. Accordingly, future research could ‘deconstruct’ the package, and investigate which aspects of the training were most effective, and which need revision. For example, giving groups only AF or KR feedback to compare their efficacy (in the present studies the effect of these two methods cannot be separated), individually trialling the goal-based and exploratory VEs, or varying the number of treatment sessions between groups.

Trials among Other Populations

Previous research has documented improvements in motor function from VR-training among other neurologically-impaired populations. For example, stroke (e.g. (Adamovich, et al., 2004; M. Holden, et al., 2007; Piron, et al., 2005), Parkinson's disease (see (M. Holden, 2005) for review) and dementia patients (Blackman, VanSchaik, & Martyr, 2007). Furthermore, younger patient groups (e.g. developmental coordination disorder, cerebral palsy, childhood stroke) are a potential target for VR-rehabilitation (Jannink, et al., 2007). The success of our system with TBI patients suggests scope for including other populations in future trials.

Remote Administration

Another possibility with VR-rehabilitation remote administration (whether in patients' homes, or remote rehabilitation facilities) allowing greater access to rehabilitation resources (M. Holden, 2005; Rizzo, et al., 2004). Future studies may remotely deliver the Elements training to assess its efficacy without a therapist present to administer it. This remote VR-rehabilitation has been investigated using teacher-animation studies (M. Holden, et al., 2007; Piron, et al., 2004). These studies both included web-cam conferencing to allow the therapist to monitor performance, and found that even when administered remotely, VR-training significantly benefited participants' motor function. This supports the possibility of remote trials of the Elements system in the future.

Inclusion of Brain Imaging Technology

To further explore whether VR-training facilitates NP for TBI patients, brain-imaging technology may be applied in future trials. For example, fMRI and PET scans have previously documented neurological changes following cognitive and physical rehabilitation of TBI (see (Laatsch, 2007) for discussion). Furthermore, the Jang (2005)/You (2005) study (discussed above) demonstrated neurological change in stroke patients following VR-training with fMRI scans, and supports the inclusion of this technology in future research.

Summary and Conclusion

The aim of the Elements project was to design, create, and test a VR- program for use in upper-limb rehabilitation among TBI patients. The program was based on the ITE ecological model of motor movement, and both challenged participants' motor planning, and provided AF. The efficacy of this system was trialled in two studies conducted at Epworth

Hospital among TBI patients. Both the initial case-studies and subsequent within-groups trials produced positive results. Participants demonstrated significant improvements in upper-limb, and neurobehavioral function following our VR-training. However, the designs of these studies preclude causal conclusions about the system's efficacy, and further group-based trials are still required. Nevertheless, results of this thesis indicate that VR-rehabilitation may be effective in retraining TBI patients' motor control, and is a promising area for future development, and research.

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APPENDICES

Appendix A. Consent form- Study 1 and 2

EPWORTH HOSPITAL

Appendix A: Participant Consent Forms, Study 1 & 2

Epworth

***Elements*:** Clinical Design and Evaluation of a Virtual Reality Augmented Workspace for Movement Rehabilitation of Traumatic Brain Injury.

Consent form

I, ..., have read and understood the information contained in the Plain Language Statement regarding the project titled '***ELEMENTS*: Clinical Design and Evaluation of a Virtual Reality Augmented Workspace for Movement Rehabilitation of Traumatic Brain Injury**'.

I understand that:

- This study is a quality improvement project and is for research purposes.
- My participation in this project is voluntary and that I am free to withdraw at any time, and free to withdraw any unprocessed identifiable data previously supplied.
- I am required to interact with a computer program by performing arm and leg movements. I understand that standardised analyses will be conducted to assess my movement abilities.
- I understand that video footage will be taken during my participation in this project.
- The results and data will remain confidential and that only the researchers will have access to the information. I also understand that the research results may be presented at conferences and published in journals, on condition that my name is not used. I am aware that there are legal limitations to data confidentiality.
- I may contact the researchers at any time, and any questions I have asked have been answered to my satisfaction. I also understand that I may contact the Human Research Ethics Committee of Epworth Hospital or RMIT University if I have any concerns.
- I understand that Peter Wilson is the Principal Researcher in conjunction with Nick Mumford and Jonathan Duckworth.
- This form will be retained, once signed, by the principal researcher.

NAME OF PARTICIPANT (in block letters): ....
Signature: .... DATE: ....
PRINCIPAL RESEARCHER: Dr. Peter Wilson
Signature: .... DATE: ....

Appendix B. Plain Language Statement (PLS)

Note: This PLS was used for both studies, with the text modified in Study 2 to describe the within-groups methodology.

Epworth

EPWORTH HOSPITAL

Elements: Clinical Design and Evaluation of a Virtual Reality Augmented Workspace for Movement Rehabilitation of Traumatic Brain Injury

Plain Language Statement

Primary Investigator: Dr. Peter Wilson (Associate Professor, Psychology, RMIT University, peter.h.wilson@rmit.edu.au, 9925 2906)

Associate Investigators: Nick Mumford (PhD student, Division of Psychology, RMIT University, nicholas.mumford@student.rmit.edu.au)
Jonathan Duckworth (PhD student, Creative Media, RMIT University, jonathan.duckworth@rmit.edu.au)

Dear Participant,
You are invited to take part in a research project being conducted at Epworth hospital. This information sheet describes the project in straightforward language, or 'plain English'. Please read this sheet carefully and be confident that you understand its contents before deciding whether to participate.

Why is this study being conducted?

The aim of the Elements Project is to design, develop and evaluate an interactive virtual environment that supports movement assessment and rehabilitation for patients recovering from Traumatic Brain Injury (TBI). This specific component of the Elements Project is designed to test the effectiveness of the Elements program using a small group of TBI participants.

Who can participate?

You can participate in the study if you are aged from 18 to 50 years, can provide informed consent to participate in this study, and have a score of 2 or more for muscle activity on the Oxford scale.

If I agree to participate, what will I be required to do?

Our project involves three stages. First, your performance on upper and lower limb tasks will be assessed regularly over one to three weeks (each of the sessions taking approximately 30 minutes). Second, you will be asked to use our training program three times a week, for four weeks, while still doing your normal therapy (each session will be 1 hour). The program involves moving objects using arm movements. You will be seated at an adjustable desk with a large LCD screen displaying the training environments. You will be able to interact with the environment in a natural and engaging way by manipulating hand-held objects and simple movements. We will track your movements using a special camera and provide feedback to help improve your physical skills. Third, we will again measure motor proficiency at regular intervals for 2 weeks (like the first stage).
To help us assess your progress in therapy, you will also be asked to complete some quick tasks that assess upper and lower limb skill. These tasks will be given after each session and are as follows: the *Box and Block Test, the MAND test*. We would also like to interview you regarding your

experience using Elements. This will involve us filming you using the program, so we can replay it later and get you to describe your experience while watching yourself on video. This will be conducted at the Epworth hospital, and each session will take between 45 and 50 minutes.

Are there any risks or disadvantages associated with participation?
No. This study is testing a program designed to enhance current rehabilitation routines, and will not involve any activities that are more strenuous or risky than your normal therapy. Additionally, the standard Epworth hospital rehabilitation safety procedures will be used.

What will happen to the information I provide?
To maintain your privacy, your results on the *Elements* program will be coded and stored on a computer at RMIT and secured with password access for 5 years. The scores for the standard evaluations will be stored in a lockable filing cabinet in the Division of Psychology, RMIT City Campus, and shredded after 5 years. No findings that could identify you will be published. Only the investigators will have access to the research data. All data and results will be handled in a strictly confidential manner, under guidelines set out by the National Health and Medical Research Council. The chief investigator is responsible for maintaining this confidentiality. This project is subject to the requirements of the Human Research Ethics Committee of the Epworth Hospital and the RMIT University. However, you must be aware that there are legal limitations to data confidentiality.

Can I withdraw from the study if I wish?
Since your participation in this study is voluntary, you can withdraw from the study at any time, and have any unprocessed data previously supplied by you removed. If you decline the invitation to participate or decide to withdraw from the study, your current rehabilitation treatment will not be affected. Following the completion of this study, a brief summary of the results will be available to you on request.

What if I have any concerns during the study?
The investigators will be available throughout the study if you have any questions. This project has been approved by the Human Research Ethics Committee of Epworth Hospital. If you have any complaints you should contact the Human Research Ethics Committee, Epworth Hospital, Ph: 9426 6755.

Whom should I contact if I have any further questions?
Any questions or concerns regarding this study should be directed to the Chief Investigator, Dr. Peter Wilson (details provided above). The investigators also encourage prospective participants to discuss participation in this study with their family or physiotherapist, should you wish to.

Yours Sincerely,

____
Dr. Peter Wilson - PhD.

____
Mr. Nicholas Mumford - B.AppSc (Psychology) (Hons)

____
Mr. Jonathan Duckworth – BSc Hons, MA (Design)

Appendix C. Published Articles

Brain Injury, March 2009; 23(3): 179–191

informa healthcare

REVIEW

Virtual reality in acquired brain injury upper limb rehabilitation: Evidence-based evaluation of clinical research

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(Received 1 July 2008; revised 10 December 2008; accepted 13 December 2008)

Abstract

Primary objective: Acquired brain injury (ABI) is associated with significant cognitive, behavioural, psychological and physical impairment. Hence, it has been important to leverage assessment approaches in rehabilitation by using current and emerging technologies, including virtual reality (VR). A number of VR rehabilitation programmes have been designed in recent years, mainly to improve upper limb function. However, before this technology gains widespread use, evaluation of the scientific evidence supporting VR-assisted rehabilitation is needed. The present review aimed to assess the rationale, design and methodology of research investigating the clinical impact of VR on ABI upper-limb rehabilitation.

Research design: A total of 22 studies were surveyed using a Cochrane-style review.

Research methods: Studies were classified on a number of key criteria: theoretical bases and aims, sample populations and recruitment procedures, characteristics of the VR systems, evaluation design including control procedures and statistical analysis of results. Studies were rated using the Downs and Black (DB) scale.

Results: The review demonstrated that few studies used a conventional randomized controlled study design. Moderate support was shown for both teacher-animation and game-like systems.

Conclusion: While VR-assisted rehabilitation shows early promise, clinicians are advised to be cautious about adopting these technologies before adequate data is available.

Keywords: *Traumatic Brain Injury (TBI), virtual reality, rehabilitations, systematic review, stroke*

Background

Acquired brain injury (ABI) is an umbrella term that refers to cerebral injury caused either by external physical force, known as traumatic brain injury (TBI), or stroke [1]. ABI results in various cognitive, behavioural, psychological, sensory and physical disabilities [1]. Disruption to motor networks impacts the ability to plan movements and to translate intentions into controlled action. Functional movements of the upper and lower extremity are commonly affected. However, modern rehabilitation procedures such as constraint-induced movement therapy have greatly enhanced patients' ability to re-acquire skills, including ability to reach, grasp and perform activities of daily living (see [2] for review). This trend will continue with the application of new technologies, such as virtual reality (VR).

Virtual reality refers to a combination of computer hardware and software used to create a virtual environment (VE), which the user interacts with in real time using their natural senses and skills. Further, VR promotes a sense of participation within the VE: VR programs allow clinicians or researchers to present relevant stimuli imbedded in a meaningful and recognizable context and engage the participants cognitively, as well as physically [3–5]. VR technology has been successfully applied in different areas of health science in recent times. For example, VR has been used for

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ISSN 0269–9052 print/ISSN 1362–301X online © 2009 Informa Healthcare Ltd.
DOI: 10.1080/02699050802695566

exposure therapy for post-traumatic stress disorder and phobias [6] and to help people with an intellectual disability learn activities of daily living (for example [7]).

A number of advantages to VR-augmented ABI rehabilitation have been proposed, which on the face of it have appeal to therapists and those interested in the science of movement. Broadly, it has been suggested that VR can increase the generalizability of treatment gains outside the rehabilitation setting by creating detailed, realistic environmental and task simulations. This capacity is valuable for retraining tasks that are potentially hazardous, such as cooking or navigation in urban settings [8]. Presentation of novel tasks and those graded according to individual needs can engage the patient and improve motivation. Performance data can also be collected automatically, providing therapists with an easily referenced record to chart recovery and a means of communicating *knowledge of results* to the patients themselves. Finally, learning curves can be enhanced by provision of augmented feedback. For example, to re-train arm function, Piron et al. [9] used augmented feedback by displaying an optimal arm trajectory during task performance.

A working assumption of VR-assisted therapy is that it can be used in rehabilitation facilities to effect meaningful change. This assumption should not be accepted at face value. If VR technologies are to find broad appeal, their benefits need to be demonstrated through controlled intervention research. Indeed, the notion of evidence-based practice places an expectation upon therapists to use treatments that are shown to have the greatest potential for recovery. Moreover, the ecological validity of VR-rehabilitation must be established to support its implementation. Without empirical support, it is difficult to justify the additional development time and cost of administering alternative treatments.

A variety of VR rehabilitation programs have been developed and tested over the past 10 years or so and several reviews have summarized this emerging body of work [8, 10–14]. These review papers have not critically evaluated the literature. Rather, they have largely adopted a descriptive, narrative approach, outlining the broad advantages of VR over traditional methods and the different ways this technology has been used to offer rehabilitation solutions. The general conclusion is that, once implemented successfully, VR technology will greatly advance ABI rehabilitation. However, a critical review by Henderson et al. [10] did question this conclusion, citing limitations in the design of VR rehabilitation studies—for example, lack of randomized controlled trials and no stratification of participant groups based on cognitive and physical functioning. However, this study focused only on VR rehabilitation among stroke patients and covered six studies. Since rehabilitation facilities frequently treat stroke and TBI patients (often with similar procedures [2]), evaluation of VR-based rehabilitation among both TBI and stroke patients is clinically relevant. Henderson et al. also included the PEDro scale to assess methodological quality in their review. Although this is an established rating scale, it is designed to assess large sample RCTs, rather than small sample studies. Since VR-assisted rehabilitation is still an emerging research field, the majority of studies are likely to be small sample. Thus, a comprehensive systematic review, based on a rating scale appropriate to small and large sample studies, both stroke- and TBI-related, is warranted.

Objectives

The first aim of this review is to describe the types of research that have been conducted to evaluate VR-augmented rehabilitation of upper-limb function among ABI populations. The second aim is to establish the quality of this research evidence using a standardized rating scale—the Downs and Black (DB) rating scale.

Methods of review

Search methods for identification of studies

Electronic databases. The following electronic databases and academic search engines were most recently searched in June 2008: ScienceDirect; ProQuest; Wiley Interscience; PsychInfo; MEDLINE; PubMed; EBSCOHost (which included the CINAHL database), PEDro, Cochrane and Google Scholar.

The following search terms were used (searches were limited to English language articles):

(1) *Technology-related terms*: Virtual Reality, Augmented Reality, Mixed Reality, tele-rehabilitation, simulation, computerized.
(2) *Diagnostic*: Acquired brain injury/ABI, stroke, traumatic brain injury/TBI, head injury/closed head injury, head trauma, brain damage/lesion/wound/injury, skull fracture, accident, car accident/collision, cerebral aneurysm, thrombosis, embolism, cerebrovascular accident, anoxia, concussion, hemiplegia, hemiparesis.
(3) Treatment: Rehabilitation, intervention, therapy, activities of daily living/ADL, upper limb/arm function, reaching, virtual rehabilitation, neuro-rehabilitation, occupational therapy,

physical therapy/rehabilitation, neuromotor, coordination, dexterity.

Initially, titles were searched using combinations of terms from each category above. As well, combinations of terms from two of the three categories were also title searched. Following an initial search of databases, the names of authors who were identified as having published relevant papers on the rehabilitation of ABI were also used for keyword searches.

Other sources. The reference lists from relevant articles were used to identify other articles and authors. Furthermore, a number of journals that frequently publish articles on ABI were hand searched: *Brain Injury*, *Cyberpsychology and Behaviour*, *Presence*, *Journal of NeuroEngineering and Rehabilitation*, *Neurorehabilitation*, *Archives of Physical Medicine and Rehabilitation*, *Journal of Head Trauma Rehabilitation*, *The American Journal of Occupational Therapy* and *Assistive Technology*. Web-based search engines (Google, Yahoo) were also searched for published conference proceedings in the field. The following search terms were added: conference, proceedings, IEEE.

Selection criteria to determine study relevance

During the literature search, articles were identified as potentially relevant based on the inclusion of searched terms in their title. The abstracts of these articles were then read and, if necessary, full-text versions were acquired. The following selection criteria were used to identify relevant studies:

Intervention research. This review sought to identify all studies that aimed to use and evaluate VR technology to improve upper-limb function among ABI patients. This search included randomized or quasi-randomized controlled trials, pre–post test trials, small-*n* studies and case studies. Only articles that evaluated the benefits of VR intervention by comparing participants' functioning before and after treatment were included. Thus, papers that merely proposed the use of VR-augmented therapies or described the theoretical and design details of such programs were not reviewed.

Participant group. Only studies that included participants recovering from an ABI (either stroke or TBI) were reviewed.

Type of intervention. Selected intervention studies were those using VR-based systems (based on the description above) designed to improve upper-limb function in ABI participants. Therefore, articles that only described VR-rehabilitation programs, tested computer-controlled robotics systems without accompanying VR training or trialled VR-based assessment (but not therapeutic) programs, were not included.

Types of outcome measure. Due to the inclusion of both randomized controlled trials (RCT) and case-studies in this review and the focus on upper-limb function, any measure of movement control, learning or skill was deemed appropriate as an outcome measure.

Assessment of methodological quality of included studies

The Downs and Black (DB) rating scale [11] was used to assess the methodological quality of the studies reviewed. This scale was chosen since it can be used for both RCT and case-study research (the central factor in selecting the DB scale over more popular ones, such as the PEDro scale) and has sound psychometric properties. The DB scale consists of 27 items (full information can be found in [11]). An example item is; 'Is the hypothesis/aim/objective of the study clearly described?' For each item on the scale, a study scored '1' if it met the criterion or '0' if it did not or it was unclear; some items were weighted higher and were scored on a 3–5 point scale. The maximum score for the DB scale is 31, with higher scores denoting better methodological quality. The DB scale is also broken down into five sub-scales: Reporting (whether sufficient information was provided in the paper to permit a full evaluation of the findings), External validity (whether the results can be confidently generalized to the wider population), Bias (whether precautions were taken to prevent bias in the way interventions were administered and measurement of outcomes), Internal validity/Confounding (whether any bias is present in the selection and distribution of participants for the study) and Power (whether the negative findings from a study could be due to chance, based on sample size).

The DB scale has adequate reliability and validity. Significant internal consistency was demonstrated, $KR_{20} = 0.89$. The test–re-test and inter-rater reliability, assessed over a 2-week interval, were also significant ($r = 0.88$, and 0.75, respectively) [11]. The DB scale items were developed in consultation with epidemiologists and medical statisticians, demonstrating its face validity. Finally, the scale's criterion validity was verified by its high correlation with the Standards of Reporting Trials Group checklist, $r = 0.90$.

It took between 10–25 minutes to score each article. The magnitude of the scores generated by the DB scale was interpreted using the following criteria; scores >20 were 'good'; between 11–20 were 'moderate' and those <11 were 'poor' [12]. The included studies were assessed by two raters (NM and PW). The raters independently scored each article and then compared their results. In the case of discrepancies of three or more points, both raters together reassessed the articles and the scores were discussed until a consensus was reached.

Evaluation of control procedures

It should be noted that while the DB scale does not evaluate the types of control procedures used in a study, since the type of control procedures applied bear on the quality of results, this information was included in the results tables and discussion.

Results

Descriptive results of the search

The search yielded 22 articles for review. Despite targeting both TBI and stroke research, 21 studies meeting the selection criteria were conducted among stroke patients. One study used 'ABI patients', the specific brain injuries experienced by participants were not detailed [13]. However, the age range of these participants (16–37 years) would suggest TBI patients rather than stroke. The majority (15) of studies used small-sample or case-study designs. The total number of participants in each study ranged from 1–50, with a mean of 11. This research was typically conducted at a university or hospital. However, many studies did not specify the setting of their research (for example [14]). The authors were unable to calculate exact descriptive age data due to several studies not providing sufficient age information (for example [15–17]). The mean age calculated from the 10 studies with sufficient information was 58 years (SD = 7.1). For the full complement of studies, it is estimated that the mean age was closer to 50 years.

Results for all studies based on DB ratings

Table I details the overall and sub-scale DB scores for the reviewed studies. The average DB score for the 21 articles was in the moderate range. Table II contains the number of articles published by year and their corresponding DB score means and ranges.

Table I. DB scores and percentages for all reviewed articles.

DB sub-scale	DB sub-scale score (mean score/possible total)	% Score
Reporting	5.8/10	58
External validity	0.27/3	9
Bias	3.95/7	56.4
Internal validity/confounding	0.8/6	13
Power	3.1/5	62
Total	13.92/31	44.9

Table II. Number of relevant articles published by year, and their corresponding DB scores.

Year	Number of articles published	DB score range	DB score mean
1999	1	10	10
2000	0	–	–
2001	3	9–14	11.7
2002	2	9–19	14
2003	1	15	15
2004	3	10–15	12.7
2005	1	23	23
2006	2	7–9	8
2007	8	9–22	16
2008	1	13	13

Effectiveness of VR-based rehabilitation in the treatment of upper-limb function

Types of VR-based system. Studies concerned with rehabilitation of arm function fell into two distinct types: the first were interventions based on game-like VR programs and the second were based on teacher-animation (where participants copy a movement demonstrated by a virtual tutor embedded within the VR program). A brief description of each VR system has been included in the results tables to provide information on the types of activities patients engaged in during therapy. However, the individual articles or the descriptive reviews discussed previously should be consulted for further details.

Game-like systems targeting arm function. In line with the prevailing assumption of researchers (that VR will make rehabilitation enjoyable and improve patients' motivation for therapy generally), many programs make judicious use of (video) game-like interactivity to develop arm function. These systems required participants to use motor movements to interact with a novel and engaging VE and achieve an outcome goal relative to the context of the game. For example, one of the four tasks trailed in the Rutgers group studies [3, 18–20] required the participant to close their fist as quickly as possible to 'scare away' a butterfly. In another, participants moved their hand across the flat display to wipe the screen clear and reveal an image. These activities targeted hand strength, speed, range of motion and finger fractionation [3, 18–20]. Other studies required participants to reach and touch targets in the VE [21, 22]. For example, Yeh et al.'s [15] system required participants to reach to touch coloured squares seen in the VE. Alternatively, participants in Broeren et al.'s [23] study used a haptic feedback stylus to hit a ball in the VE against a wall of bricks. The goal was to volley the ball back and forth to remove the bricks and reveal a picture. A later study used a similar stylus interface device [18], however the goal was to reach to push circular buttons seen in the VE as quickly and accurately as possible.

Of those nine studies that employed game-like designs, seven would, statistically, be considered small-*n* designs and two large sample studies (see Table III for references) [19]. However, it is acknowledged that sample sizes of 15 and 29 may not be considered large in many research fields and larger samples are a priority for future VR-therapy research. All studies involved stroke patients. Four of these articles were from a group at Rutgers University and investigated the same technology [3, 18–20]. The mean DB score for the game-like systems was 11.9, indicating moderate support. Table III shows individual DB scores and study details.

Teacher-animation arm function systems. Thirteen arm function programs were based on teacher-animations (see Table IV for references). These systems all incorporated an animation into their VEs to guide participants' movement during task performance. These animations may be a complete arm (for example [14]) or simply a cursor viewed in the VE (such as [24]). Of the teacher-animation articles, 10 were from two research groups—Holden and Piron. These programs use an animation to model how participants should perform the task. The theoretical underpinnings to each approach were somewhat different. Holden and colleagues based their design on the theory that people plan arm movements based on end-point trajectory. Thus, their system used teacher animations to demonstrate the endpoint trajectory of movements during task performance, assisting participants to better plan their actions. The Holden studies used a virtual teacher (a limb-like representation projected into virtual space) to demonstrate endpoint trajectory while mailing a letter or pouring water in the VE. Piron et al. argued that teacher animations provide augmented performance feedback, helping to guide participants' movement patterns. Augmented feedback is the provision of movement information, over and above the normal flow of visual and movement-related (or kinaesthetic) feedback. Therefore, augmented feedback can help focus participants' attention on improving specific aspects of movement, for example accuracy. Accordingly, in these studies participants used real objects (such as an envelope) equipped with a magnetic tracking receiver to move a cursor seen in the VE through a series of targets set by the therapist. Other programs were not goal-directed, requiring participants to mimic the actions of the teacher-animation in virtual space. For instance, participants in Gagglioli et al.'s [14, 25] research performed a reaching movement with their less-effected arm, which was recorded by the system then inverted and replayed on a horizontal display to provide the teacher animation for their more-impaired arm. Participants would then replicate the movement with their impaired arm, over the animation. The program measured discrepancies between the animation and the movement with their impaired hand.

The majority of these studies (8) were conducted using small-*n* designs. The mean DB score for these articles was 15.2, indicating moderate support for teacher-animation systems. The study details and DB scores are presented in Table IV.

Summary

Overall, the broad aim to improve general arm function among ABI populations was moderately supported by the complement of studies. Although both game-like and teacher animation systems received moderate support, the latter scored higher. However, an independent samples t-test (conducted based on equal variances following a Levene test, $p = 0.453$) demonstrated no significant difference in DB score between the two groups, $t(17) = 0.908$, $p = 0.376$, $d = 0.40$, 95%CI (−0.51, 1.31).

Discussion

The findings of this review indicate that research on the effectiveness of VR-based upper limb rehabilitation in ABI is still exploratory. Despite innovations in the design of the VR systems, research has been largely conducted using uncontrolled, small sample designs. Furthermore, an exhaustive search indicated that studies were almost exclusively conducted on stroke patients. This highlights a pressing need to include TBI populations in this research in order to support the application of VR-based technologies to the wider ABI population. Based on the DB scale results, there is moderate support for this technology. On this basis, more rigorous studies are warranted to further investigate the conditions

Table III. Details for studies aiming to improve upper limb function using game-like VR systems.

Article	Description of VR system: interface device & workspace	Severity of ABI and any clinical measures*	Recruitment procedures	Control groups used	Outcome variables*	Duration of intervention	Statical analyses	Results of intervention	DB score
Adamovich et al. [20]	4 VR tasks, viewed on a flat PC-monitor Tasks 1–3 (below) use a data glove interface device. Task 4 uses Rutgers Master II glove, which has force resistors attached to each finger. Task 1: move hand from side to side to 'wipe clear' a window and reveal a picture. Task 2: close fist to scare away a butterfly. Task 3: move fingers to play a 'virtual piano'. Task 4: move fingers at set strength.	Left hemisphere stroke occurring >1 year post-stroke	8 stroke patients, no recruitment info	None	JTAF, Range of motion (ROM), finger fractionation, speed, hand strength (measured by system)	13 days	t-tests, ANOVA, between pre–post test data	Significant improvements for 6 participants in ROM, 7 in finger fractionation, 4 in speed and 3 in strength. Significant improvements in JTAF	15
Boian et al. [21]	Same system as Adamovich et al. [20]	Right hemiplegic stroke, 1–4 years post-stroke	4 stroke patients, no recruitment info	None	JTAF, Range of motion (ROM), finger fractionation, speed, hand strength (measured by system)	3 weeks, 5 sessions per week	None, percentage improvements pre–post test reported.	3 participants improved ROM, finger speed. Four participants improved fractionation. Two participants improved in JTAF	9
Broeren et al. [23]	VE viewed on a PC-monitor through 3D glasses. Patient uses a haptic feedback stylus as the interface device. VR task: volley a ball back and forth, removing bricks at the back of the VE and reveal a picture.	Right side stroke, >12 weeks post–stroke	1 stroke patient, no recruitment info	None	PPT, hand strength	4 weeks, 12 90-minute sessions	None, raw pre–post test scores presented	Improvements in PPT, and hand strength	10
Broeren et al. [18]	VE viewed on a PC-monitor through 3D glasses. Patient uses a haptic feedback stylus as interface device. 6 VEs each containing a point and click task.	Stroke, 1–140 months post-stroke	29 stroke patients, no recruitment information	Stroke group and healthy control group	Hand speed, accuracy and hand path ratio (measured by system)	No details provided	None, results were verbally described, one box and whisker plot provided	Patients scores on all variables were said to improve. Comparison with control group not detailed and magnitude of improvement not supplied	13

Fischer et al. [22]	VE viewed through a head mounted display. Data glove used as the interface device. VR task: to reach and grasp 3D objects seen in the VE.	Stroke, 1-year post-stroke, FMA and CMSA scores pre-test	15 stroke patients, volunteers, source unknown	3 groups, cable orthosis, pneumatic orthosis, control	Hand ROM and strength, task performance, FMA, WMT, BBT, RLA	6 weeks, 1 hour session 3 times per week	ANOVA between groups pre–post-test	Treatment groups significantly improved in WMFT. No significant improvements in RLA, ROM, FMA, BBT strength, task performance	20
Jack et al. [29]	Same system as Adamovich et al. [20]	Left hemisphetic stroke, 3–6 years post-stroke. FMA, JTAF scores pre-treatment	3 stroke patients, no recruitment info	None	Range of motion (ROM), finger fractionation, speed, hand strength	9 60–90 minute sessions	None, raw scores pre-post-test provided	All participants improved across all variables	12
Kuttuva et al. [30]	VE viewed on PC-monitor. Tracking sensor attached to patient's wrist was the interface device. VR task 1: grasp, lift, place VR objects. Task 2: volley a ball back and forth removing bricks at the back of the VE.	Left middle cerebral artery infarct, 17 months post-stroke	1 stroke patient, no recruitment info	None	FMA, wrist displacement, arm speed	4 weeks, 3 sessions per week	None, raw scores pre-post-test provided	The participant improved on all variables	7
Stewart et al. [32]	VE viewed on a PC-monitor, through 3D glasses. Tasks 1&3 used a magnetic tracker on participant's hand as the interface device. Task 4 used two haptic sensors, one on the forefinger and one on the thumb. Four VR tasks. Task 1: reach for cubes and hit one cube at a time. Task 2: reach to intercept a ball shot from the wall in the VE. Task 3: reach to touch targets in the VE. Task 4: pick up and move cubes with thumb and forefinger.	Hemiparetic stroke, >1 month post-stroke	2 stroke patients, no recruitment info	None	FMA, BBT, FTHUE, SIS	3 weeks, 4 1–2 hour sessions per week	None, percentage change pre–post-test provided	Both participants improved in FMA, BBT, FTHUE, SIS. Only one participant improved BBT score	12
Yeh et al. [15]	Same system as Stewart et al. [32]	Severity not described	5 stroke patients, recruited from University of Southern California	None	*Movement efficiency*, movement speed and task performance time	12 2 hour sessions	None, pre–post-test results presented graphically for one participant	All participants improved across all variables. However, supporting data for only one participant provided	9

* See Appendix for abbreviations of measures.

Table IV. Details for studies aiming to improve upper limb function using teacher animation-based VR systems.

Article	Description of VR system: interface device & workspace	Severity of ABI and any clinical measures*	Recruitment procedures	Control groups used	Outcome variables*	Duration of intervention	Statical analyses	Results of intervention	DB score
Gaggioli et al. [14]	VE displayed on a horizontal screen. Tracking sensors on the hand used as the interface device. Task: match arm movement of their more disabled arm to the recording of the same movement made with their better-recovered arm.	Right hemisphere stroke 19 months post-stroke	1 stroke participant, no recruitment info	None	FMA, ARAT	4 weeks, 3 sessions per week	None, percentage change on outcome measures provided	Participant improved both FMA and ARAT scores post-test	9
Gaggioli et al. [25]	Same system as Gaggioli et al. [14]	Stroke, 1–6 years post-stroke, all experienced hemiplegia	9 stroke patients, recruited from local rehabilitation facility	None	FMA, ARAT	8 weeks, 3 sessions per week	*t*-tests on pre-post test data	No significant improvement	18
Holden et al. [33]	VE displayed on PC-monitor. A real letter with attached tracking marker was the interface device. Task: to copy the actions of a VR animation demonstrating a movement to post a letter.	Cerebrovascular accident, 1–4 years post-stroke. FMA scores pre-treatment	2 stroke patients, no recruitment info	None	FMA, SAILS	16 1–2 hour sessions	None, numeric and percentage variation provided	Minor improvement on both measures	10
Holden et al. [13]	VE displayed on PC-monitor. A real water jug with a sensor attached was the interface device. Task: to copy the actions of a VR animation demonstrating how to pour water from a jug.	ABI, 3–18 years post-incident. FMA scores pre-treatment	4 ABI patients, no recruitment info	None	FMA, ETUEF	32 sessions	None, pre–post test percentage improvement provided	Minor improvement in both measures	9
Holden et al. [27]	Tested the systems used in Holden et al. [13,33]	Stroke, 6 months–4 years post-stroke. FMA scores pre-treatment	7 stroke patients, no recruitment info	None	FMA, WMT	10 weeks, 3 1 hour sessions per week	None, pre–post test percentage change provided	All participants improved pre–post test on both measures	14
Holden and Dyar [28]	VE displayed on a PC-monitor. A tracking sensor on participant's hand was the interface device. Task: to copy basic movement patterns (e.g. reaching) made by the virtual teacher animation.	Stroke, several years post-stroke. FMA scores pre-treatment	9 stroke patients, no recruitment info	None	FMA, WMT	10 weeks, 3 1 hour sessions per week	*t*-tests performed on pre–post test data	Significant improvement on FMA. Significant improvement on 2 sub-scales of WMT	19
Holden et al. [34]	Same system as Holden and Dyar [28].	Stroke >6 months post-stroke	11 stroke patients, no recruitment info	None	FMA, WMT	10 weeks, 3 1 hour sessions per week	ANOVA tests performed on pre–post test data	Significant improvement for all participants on both measures	20

Montagner et al. [16]	VEs displayed on a large projector screen. Force feedback exoskeleton used as interface device. 3 VR tasks. Task 1: Reach to touch buttons seen in the VE. Task 2: trace circle targets displayed in the VE. Task 3: Rearrange cubes in the VE to make a picture.	Stroke, >1 year post-stroke	3 stroke patients, no recruitment info	None	Movement smoothness (measured by the system)	6 weeks, 3 1 hour sessions per week	None, graphical and numeric changes provided	Improvement in movement smoothness pre–post test	9
Piron et al. [17]	VE displayed on a flat wall screen. Real objects with tracking sensors were the interface devices. Task: to move real objects (envelope, hammer, drinking glass) to match a virtual arm movement.	Stroke, >3 months post-stroke	24 stroke patients, no recruitment info	Conventional therapy, VR therapy groups	FMA, FIM	5–7 weeks, 5 1 hour sessions per week	Wilcoxon tests used to assesses within group change, Mann-Whitney U-tests assessed between groups change	Both groups improved significant pre–post test. No significant between groups change	15
Piron et al. [9]	Same system as Piron et al. [17].	Ischemic stroke, >1 year post-stroke	5 stroke patients, no recruitment info	None	FMA, FIM	4 weeks, 5 1 hour sessions per week	Wilcoxon tests used to assesses within group change	Significant improvement in FMA score, no significant change in FIM scores	13
Piron et al. [35]	Same system as Piron et al. [17]. However, an extra task (putting a ball in a basket) was included.	Ischemic stroke, >6 months post-stroke. FMA scores pre-treatment	50 stroke patients, recruited from their rehabilitation facility	None	FMA, FIM	4 weeks, 5 sessions per week	Wilcoxon tests, Mann–Whitney U test, Spearman's Rho correlations	Participants demonstrated significant improvement between pre–post test	23
Piron et al. [24]	Same system as Piron et al. [17].	Stroke, <3 months post-stroke	38 stroke patients, no recruitment info	VR therapy and conventional therapy groups	FMA, FIM	5–7 weeks, 5 1 hour sessions per week	Wilcoxon tests used to assesses within group change, Mann-Whitney U-tests used to assess between groups change	Both groups improved significantly pre–post test. No significant between groups differences	18
Turolla et al. [36]	Same system as Piron et al. [35].	Stroke, >6 months post-stroke	30 stroke patients, recruited from their rehabilitation facility	VR therapy and conventional therapy groups	FMA, FIM	4 weeks, 5 1 hour sessions per week	Wilcoxon tests used to assesses within group change, Mann-Whitney U-tests used to assess between groups change	Both groups improved significantly pre–post test. VR group improved significantly more on FMA, but not on FIM scores	22

* See Appendix for abbreviations of measures.

under which VR can be implemented effectively, including: optimum scheduling and intensity of intervention, profiling those patients who are most likely to benefit from VR-training and appropriate follow-up. Such studies will ensure that this technology can be implemented with confidence in clinical settings. Of the studies reviewed, teacher-animation systems were shown to score higher on the DB scale than game-like systems. However, this difference was not significant and both groups still provide moderate support for their systems. It should also be noted that even though moderate support was attained based on the DB interpretation system used, the average score for these studies was only two points above the cut-off between 'moderate' and 'poor' studies. Indeed, many studies were classified as poor. In short, these facts emphasize the need for caution in implementing VR-based rehabilitation prior to more substantive evidence.

Assessment of overall methodology

As seen in Table II, there has been a general increase in the number of studies published over the last 9 years. The increase in publications relating to VR-augmented ABI rehabilitation is due in part to the advent of new academic conferences in neurorehabilitation and applications of VR (such as *Virtual Rehabilitation*, http://www.aristea.com/iwvr2007), indeed many studies published in 2007 were from conference proceedings. Although there is little change in the mean DB scores over time, the number of papers scoring above average for this field has increased from three studies between 1999 and 2003, to seven studies between 2003 and 2008. This may indicate a shift towards more sound research designs. However, when the control procedures and DB sub-scales are considered further, it is evident that some areas of conceptualization and methodology, like external validity, require more improvement than others, such as use of established outcome measures.

Control procedures. Although the limited number of larger-sample studies did employ control group(s), in some cases the choice of control groups did not permit evaluation of treatment effects. For example, Fischer et al. [22] divided participants into two treatment groups and one 'control'. However, all groups received VR training but with different levels of assistance in performing the reach-to-grasp activities. Thus, the efficacy of the VR system compared to normal rehabilitation was unclear. Accordingly, better use of control groups among larger sample studies is required to isolate the impact of VR therapy.

The small-*n* studies also employed control methods that did not clearly demonstrate the efficacy of VR. Traditionally, single participant designs have been used to reasonable effect in ABI research, permitting comparisons between treatment conditions over time [26]. Variations on the standard AB time-sequence design have featured previously in ABI research, where performance is measured during baseline phase(s) (A) and treatment phase(s) (B). Among those VR studies that did employ an AB method [23, 27], only a single assessment was conducted per phase. This procedure does not permit a stable baseline to be established nor evaluation of the trajectory of change; this makes it difficult to attribute improvements in function to the treatment, rather than random variations in the test environment or within the individual.

Reporting sub-scale. Generally the complement of studies rated highly on the reporting sub-scale, compared to the others (see Table I). In particular, study aims were clearly stated and characteristics of the sample and treatment populations were adequately described. However, poor identification of confounding variables, reporting of possible adverse events and description of whether participants were lost to follow-up were common limitations.

Several methodological changes could be made in the future to account for confounding variables and adverse effects in future work. Potential confounding variables include whether participants are undergoing concurrent rehabilitation and their previous experience with VR technology. Furthermore, research has documented cases of illness similar to motion sickness (termed 'cyber-sickness') following use of VR technology [28]. Although several studies did state that no participant experienced cyber-sickness, all researchers should report on this as a matter of course. The representativeness of samples can also be better determined by reporting on the number of participants who were removed or dropped out of the study and the reasons why. Finally, those studies that included statistical analyses generally did not report exact probability estimates. Reporting exact probabilities (and effect sizes with confidence intervals, where appropriate) will help temper the interpretation of significance tests, enable a more balanced discussion of results and allow accurate inter-study comparison.

External validity sub-scale. This sub-scale is based on details about recruitment procedures and the setting where the evaluation was conducted. The studies scored very poorly on this sub-scale. Many papers scored 0 for all three items and none received a full score. Thus, the external validity of this research can be considered a major limitation to date.

Although not directly assessed by the DB scale, clinical significance data that reflects functional improvement is crucial in establishing external validity. Clinical significance is the theory that an intervention may not produce statistically significant results, yet improve patients' lives (the opposite may also occur) [26]. The studies reviewed here did not report quantitative clinical significance data. Further, qualitative clinical significance information was only provided by four studies [14, 28–30]. Of these, one noted improvements in fine-motor skill [29] and three in gross-motor [14, 28, 30]. Accordingly, future research could include more evidence that VR-therapy has a real world impact on patients' lives through systematic clinical significance analysis (see [31] for discussion) and assessments of functional change.

Bias sub-scale. The studies reviewed generally scored well on this sub-scale. However, there were some inconsistencies. Almost all studies scored highly for conducting only pre-planned analyses, having consistent treatment administration, treatment adherence and utilizing sound outcome measures. Further, studies that did employ statistical procedures used tests appropriate to their aims, such as *t*-tests and ANOVA. Despite the fact that blinding participants to group may be difficult with VR technology (i.e. creating placebo systems may be impractical), blinding the administrators of treatment and assessment protocols would be possible in future studies.

Internal validity or confounding sub-scale. This sub-scale assesses whether any bias is present in the selection and distribution of participants for the study. The studies reviewed did not score highly on this sub-scale. Few researchers indicated the timeline for recruitment (over how many months and during which years) and whether they were from the same cohort (i.e. whether participants were recruited from multiple sites). As well, none attempted to conceal the allocation of participants to groups. Finally, confounding variables and drop-out rates were not well reported, creating potential sources of error.

Power sub-scale. This sub-scale rates whether the negative findings from a study could be due to chance, based on sample size. The studies scored moderately well on this sub-scale. Further, while this finding indicates that (according to the DB criteria) adequate sample sizes were used, many studies still had samples which would be considered low power [19]. Based on the DB scale a study with 10 participants would score the same as a study with 100 participants (a much higher power sample). Thus, the DB scale may give an inflated representation of statistical power. Nevertheless, by statistical standards, existing research can still be considered low power.

Limitations to review

There are aspects of the present review that could be improved. First, database searches were limited to English language studies. Peer-reviewed research published in other languages could be included in future reviews. Secondly, some items on the DB scale, such as whether participants were blind to group allocation, may be difficult to achieve with VR technology. Thus, receiving a full score on the DB scale may be unreasonable for this type of research.

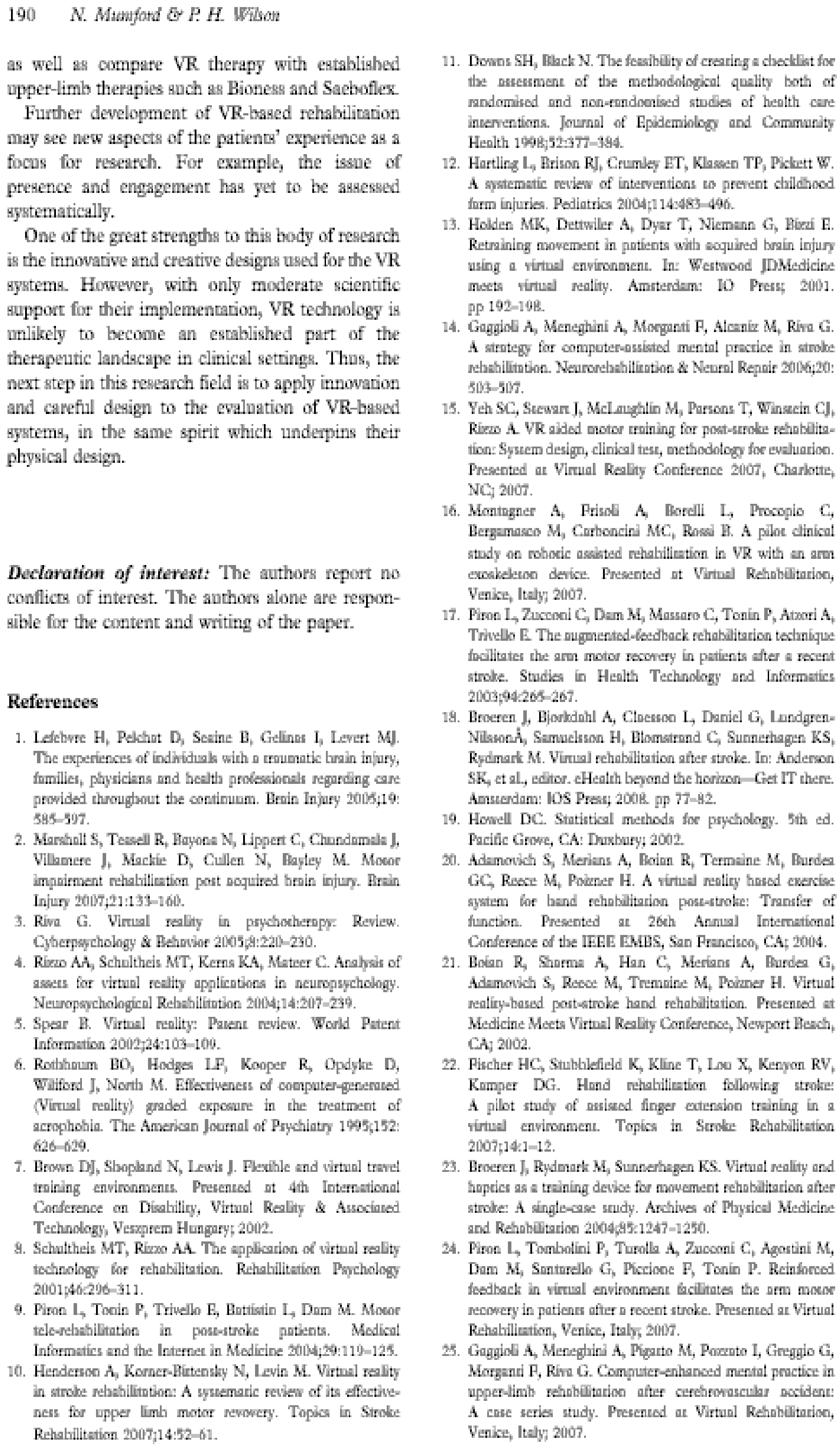
Conclusions

Implications for practice

The present results indicate greater support for teacher-animation methods as compared to game-like systems. However, both approaches lack sufficient evidence to date to recommend their clinical implementation. Furthermore, despite efforts to categorize the VR systems, there was still some variation between the designs of the VR programs within each category. Accordingly, there is a need to identify common factors between effective VR rehabilitation protocols (for example provision augmented feedback, intensity of training, type of interface device) to inform the design and implementation of new programs.

Implications for research

Based on analysis of the DB sub-scales, there is substantial room for improvement on aspects of internal and external validity. This could be accomplished by using larger sample sizes and control groups able to isolate treatment effects. Further effort to improve data analysis (e.g. effect size estimates), reporting and reduce experimental bias is needed to support the implementation of VR systems. Future studies could also investigate the impact of sensory-processing deficits on VR rehabilitation, as these types of deficit may place limits on how ABI patients interact with the system. Finally, in order to increase the clinical relevance of findings, researchers could investigate systematically the effect of VR-based rehabilitation on functional abilities,



as well as compare VR therapy with established upper-limb therapies such as Bioness and Saeboflex.

Further development of VR-based rehabilitation may see new aspects of the patients' experience as a focus for research. For example, the issue of presence and engagement has yet to be assessed systematically.

One of the great strengths to this body of research is the innovative and creative designs used for the VR systems. However, with only moderate scientific support for their implementation, VR technology is unlikely to become an established part of the therapeutic landscape in clinical settings. Thus, the next step in this research field is to apply innovation and careful design to the evaluation of VR-based systems, in the same spirit which underpins their physical design.

Declaration of interest: The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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Appendix: Abbreviations for outcome measures

- ARAT—Action Research Arm Test
- BBT—Box and Block Test
- CMSA—Chedoke McMaster Stroke Assessment
- ETUEF—Emory Test of Upper Extremity Function
- FIM—Functional Independence Measure
- FMA—Fugl-Meyer Assessment of Motor Function
- FTHUE—Functional Test of the Hemiparetic Upper Extremity
- JTAF—Jebsen Test of Arm Function
- PPT—Purdue Pegboard Test
- RLA—Rancho Los Amigos Functional Test of the Hemiparetic Upper Extremity
- SAILS—Structured Assessment of Independent Living Skills
- SIS—Stroke Impact Scale
- WMT—Wolf Motor Test of Upper Extremity Function

Brain Injury, May 2010; 24(5): 780–791

informa healthcare

Upper limb virtual rehabilitation for traumatic brain injury: Initial evaluation of the elements system

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(Received 17 June 2009; revised 12 January 2010; accepted 13 January 2010)

Abstract

Primary objective: To evaluate the effectiveness of a tabletop virtual-reality (VR) based upper-limb rehabilitation system (called Elements) for promoting movement skill in patients with TBI.

Research design: An ABA case study design with multiple baselines was employed. Baseline performance in this design is contrasted against the results during the treatment phase.

Research methods: Three patients with TBI participated in 12 1-hour sessions of VR-based training. The VR system consisted of a 42-inch tabletop LCD, camera tracking system and tangible user interface. The system requires participants to move an object to cued locations while receiving augmented movement feedback to reinforce speed, trajectory and placement. Upper limb performance was assessed using these three system-measured variables and standardized tests. Trends in the time-sequence plots for each patient were assessed by sight inspection of smoothed data and then by statistical analyses.

Results: Participants demonstrated improvements on movement accuracy, efficiency and bimanual dexterity and mixed improvement on speed and other measures of movement skill.

Conclusion: Taken together, the findings demonstrate that the Elements system shows promise in facilitating motor learning in these TBI patients. Larger scale trials are now deemed a viable step in further validating the system.

Keywords: *Traumatic brain injury, virtual reality, rehabilitation, motor learning, motor control, augmented feedback*

Introduction

Overview

The application of virtual reality (VR) to assessment and rehabilitation has gained considerable impetus in recent years. An earlier paper [1] described the development of a VR-system (called *Elements*) for use with individuals with traumatic brain injury (TBI). The Elements system uses low-end technologies to achieve stable movement tracking, flexible presentation of virtual environments (VEs), augmented feedback (AF) and automated recording of performance data. The system was designed to complement current approaches to rehabilitation. This paper presents a clinical evaluation of this programme using a single case research design with multiple baselines for three cases.

Traumatic brain injury

Individuals with TBI commonly experience disability in upper-limb function, including poor timing

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ISSN 0269–9052 print/ISSN 1362–301X online
DOI: 10.3109/02699051003652807

and accuracy of reaching and reduced ability to grasp and lift objects [2]. Impaired motor planning is also common due to damage to brain networks responsible for forming and implementing motor intentions (i.e. pre-motor cortex, parietal cortex, basal ganglia and cerebellum) [2]. This is manifested by abnormal kinematics: delayed movement latency, poor trajectory control and so on [3]. VR may provide an effective means for assessing motor control and skill and for designing rehabilitation activities. In addition, VEs can engage and motivate individuals with TBI, automate data collection and provide greater control over task constraints [4].

VR and TBI rehabilitation

The benefits of VR-based training after brain injury have been widely claimed, although most data are drawn from stroke patients (see [5] for review) and studies on TBI have generally been exploratory. Several researchers have verified the usability of VR programmes when assessing cognitive function [6, 7] and re-teaching functional skills [8–10]. Only two studies have assessed the clinical benefits of VR-based rehabilitation among individuals with TBI: one successfully improved participants' balance [11] and the other cognitive function [12].

Mixed methodologies for evaluation research

It is assumed that VR therapy can be used effectively in clinical settings. However, this remains to be fully tested in intervention research. Indeed, the notion of evidence-based practice places an onus upon therapists to use treatments with the greatest potential for recovery.

Case study methods are a vital tool for evaluating new treatments [13] and for providing justification for larger-*n* studies [14]. Time-series design involves repeated assessment of a single participant over baseline and treatment phases, permitting a detailed analysis of performance and a flexible means of testing hypotheses (see [15] on the merits of case-study research). These designs are also clinically relevant by focusing on within-person change.

The aim of the present investigation was to evaluate a new VR-based rehabilitation system designed to improve upper limb function in TBI. This study was designed to assess the efficacy of the Elements programme as an integrated rehabilitation system, using an ABA, multiple baseline case-study design. It was predicted that a 12-session course of VR-based therapy, concurrent with normal rehabilitation, would improve upper limb function in patients with TBI relative to baseline performance.

Method

Participants

Three participants with TBI were invited to take part in this study at Epworth Hospital, Melbourne by the Senior Physiotherapist. Because the Elements system can be scaled to the patient's individual skill level, inclusion criteria were broad. Moreover, at this early stage in the evaluation process, it was not deemed appropriate to test more specific hypotheses about the effects of therapy on different sub-groups of TBI patient (e.g. chronic vs acute patients). The inclusion criteria were: aged under 50 years; and a score of at least 2 for muscle activity as measured on the Oxford scale [16] (focusing on wrist/finger flexors/extensors, elbow flexors and shoulder flexors). Accordingly, each participant experienced deficits in upper-limb function and considered this rehabilitation important (evidenced by their volunteering for the 4-week training programme). Participants were also required to have the cognitive capacity to provide informed consent and to understand the VR programme. While there was no specific pre-requisite for visual acuity, using the programme required a level of vision equivalent to reading a book/magazine or watching television, which all participants could do. These participants were the first three identified by the physiotherapy team (including co-author Williams) as needing more upper-limb therapy. All consented to participate. Details for each participant are as follows:

- *Participant TJ* was a male aged 21 years. TJ's TBI occurred as a result of an automobile collision, 12 months prior to the study; his post-traumatic amnesia (PTA) lasted 75 days. During this study, TJ was first living with family and then independently as an outpatient. TJ's average score on the standardized upper-limb assessment the Box and Block test (BBT; seen to accurately represent daily functioning ability [17]) during baseline was 73 for his right (dominant) hand and 51 for his left. These scores were 1.7 and 4.1 SD below the norm for non-disabled participants between 20–24 years, respectively. TJ was undergoing physical therapy that mainly targeted balance and gait. He experienced moderate hemiparesis and dystonia in his left arm.
- *Participant SK* was a 20 year-old male who experienced TBI in an automobile collision 8 months prior to the study and his PTA lasted 88 days. SK lived with his family as an outpatient during this research. SK's physical therapy consisted of balance retraining, weight-based strength and conditioning and hydrotherapy swim training. SK's mean right (dominant) hand BBT score during baseline was 39, 5.5 SD below the norm.

His mean left hand BBT score during baseline was 45, 4.9 SD below the norm.

- *Participant AN* was a male aged 20 years. He experienced TBI as a result of an automobile collision 4 years before the study. AN's PTA lasted more than 3 months (exact length of PTA unknown) and he was an inpatient during the study. AN's status as an inpatient after 4 years was due to his accident occurring in a remote setting, several thousand kilometres from any rehabilitation facility. AN had been admitted to several hospitals across Australia and was admitted at Epworth for an initial assessment which became a 6-month period of inpatient rehabilitation. He presented with ataxia and required assistance to walk. AN underwent physical therapy on a daily basis focusing mainly on mobility and gait; upper-limb training was less intensive. AN scored a mean of 27 on the BBT for his right (dominant) hand during baseline. This value is 7 SD below the norm. His left hand BBT baseline mean was 28, 6.9 SD below the norm.

The study was approved by the Human Research Ethics Committees of the RMIT University and Epworth hospital. Additionally, all participants were undergoing OT training aimed at improving upper-limb activities common to young male patients such as self-care (showering, dressing, tooth-brushing, hair brushing, buttons, zips, shoe laces), mobile phone texting, keyboard/computer use, throwing/catching a ball, etc.

Materials

Elements system: Rationale for the programme. The Elements system draws on established theories in human–computer interaction and the science of human movement [1, 18, 19]. It blends ecological and neuroscience approaches to motor control and learning [20, 21] to create virtual workspaces for clinical assessment and rehabilitation. Ecological and dynamic systems models of movement contend that motor control is an emergent property of a biological system. Movement synergies and patterns are seen to arise from the interaction between the biological system and its environment. The perceptual systems of the mobile performer are inherently 'intelligent', which enables information about the layout of the environment and one's position within it to be extracted fairly directly. However, individual neurocognitive constraints (like attentional flexibility and executive control) also determine that action will vary between individuals over the course of development and as a result of brain pathology or trauma.

The interactive nature of movement is encapsulated by the Individual, Task, Environment (ITE) model of motor control [22]. The ITE model argues that any movement is specified by the biological constraints of the *individual* performer and their interaction with *task* and *environmental* factors. Individual constraints can be the intrinsic biomechanics of the system itself and cognitive processes. Task constraints include locomotion and stability, propulsion (of objects) and so on [22]. Environmental constraints concern both the regulatory features of the movement terrain and to-be-manipulated object(s), social supports and background conditions like noise and lighting.

The ITE model sits well in neurological rehabilitation, since the overall goal is to assist the individual (impaired in some respects) in relearning how to effectively interact with everyday tasks and environments [22]. The ITE approach is regarded as an important framework for increasing the ecological validity and generalizability of therapy [23].

The control and flexibility that VR technology provides over task and environmental constraints makes it an excellent medium for helping patients regain motor control, commensurate with the ITE model. Thus, the Elements system was designed to vary task and environmental parameters (within the context of VEs) in such a way that individual patients would be encouraged to develop new movement solutions. The means of supporting change was achieved through three main avenues: (i) the process of scaling learning environments to the individual, (ii) providing AF that helps compensate for current processing limitations and (iii) presenting aesthetically stimulating and challenging tasks that draw the user into the learning space and help motivate interaction. In short, improving participants' general ability to respond to varying task and environmental constraints was designed to increase their capacity to plan and initiate movements, to engage in normal physical and OT rehabilitation and to act in the real world.

The broad aim of the Elements programme is to develop participants' motor planning (their ability to cognitively prepare the requisite movements to achieve an action goal with some efficiency, see [24] for further discussion); as mentioned, the means to this end is a facility for scaling the difficulty of the virtual tasks and using AF. AF is the provision of information in addition to the normal flow of visual and movement-related feedback [25]. Under the ITE model, AF increases the amount of task and environmental information provided to the individual, allowing them to construct a better sense of their position in the action space, determine what variations in movement parameters (force, speed and trajectory) are needed to realize a goal and feel for the unfolding movement trajectory itself. Non-VR rehabilitation studies have found AF to be an effective approach [26, 27]. For example, stroke participants receiving auditory AF when their movement trajectory was outside normal range showed significantly more improvement in reaching speed and accuracy than a practice group [26].

The concept of using AF in VR rehabilitation has been applied successfully in other research [28, 29]. These systems have focused on using a 'teacher animation' to guide participants' movements and provide AF. Although this approach has merit, the authors contend that improvements in motor control will be more generalizable when AF is used to redevelop participants' capacity to interact with task and environmental factors. The different forms of AF that are enlisted by the Elements system are described below.

Elements system: Hardware. The Elements system runs on off-the-shelf PC hardware. The PC has an AMD Athlon64 X2 Dual Core 4400+ (2.21 GHz) processor and 2 GB RAM. The PC is equipped with an nVidia GeForce 7800 graphics card. The VE is displayed onto a 1020 mm (42 inch) LCD panel placed horizontally, with audio cues presented via stereo speakers. The panel is covered by a piece of non-reflective hardened glass (see Figure 1(a) for the system set-up). The movement of the Object (a plastic cylinder) is tracked using the Bumblebee2a camera system from PointGrey, which has pre-calibrated stereo cameras for accurate depth measurement (see also [1, 30] for the hardware comprising the Elements system). The precision of the tracking system is within 0.1 mm.

Elements system: Task description and AF. Task 1 (Bases) consists of the home base and three potential movement targets, all 78 mm in diameter. The circular targets are cued in a fixed order (west, north, east) using an illuminated border (see Figure 1(b)). Task 2 (Random Bases) has the same configuration of targets, but they are highlighted in random order. Task 3 (Chase Task) begins with a blank screen. A target circle then appears randomly in each of nine locations. These locations are configured along three radials emanating from the home base. Task 4 (Go-No-Go) uses the same target positions as Task 3, however, additional distractor targets (viz., a pentagon, triangle and rectangle) appear. Participants were instructed to place the object on the circular targets only and to resist moving to distractors.

The AF in the Elements programme was designed to serve two purposes. First, it provides participants with additional knowledge of the outcomes of their actions to aid in future movement planning. Secondly, AF allowed participants to focus their attention on the effects of their movement, rather than on the movement itself [31]. In this system, each AF feature is related to one or more of the three movement variables or task parameters. Thus, the form of AF during a task depends on which variables are targeted for improvement (see Table I for the AF options). During training, participants were instructed to focus on the AF appropriate to the performance variable that was targeted. For example, if the aim was to improve accuracy the participant was instructed to focus on the disk AF and to use it to line up the object before placing it. Accordingly, AF was provided for participants during the tasks and served as a form of 'real-time feedback', giving movement-related information during performance of each trial (as opposed to the graphs presented at the end of each session, discussed subsequently).

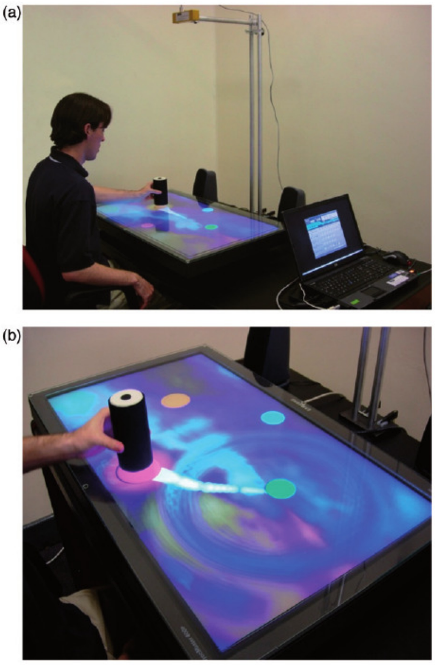

Figure 1. (a) The Elements system and (b) sample of augmented feedback showing ripple, trace and aura effects.

System-measured variables. Three performance/dependent variables are recorded automatically by the system during the tasks. Accuracy of placement is measured as a percentage score and represents the overlap between the base of the object and the

Table I. Description of the AF features of the Elements system and the movement variables related to each.

Augmented feedback (AF)	Movement variable associated with AF
Ripple effect for placement	
When the object is placed on the target, a water ripple animation emanates from that location.	Informs participants whether the object was placed correctly.
Object trace of trajectory	
As the object is moved above the screen, a fading trace follows the object's path on the monitor.	Visual representation of movement efficiency and accuracy.
Sound pitch for proximity and/or volume for speed	
(a) As the object approaches the target, a tone increases in pitch (and loudness). (b) Movement speed is also correlated with a second source of sound; here pitch can be selected to increase with speed. (c) A final 'click' sound is emitted when the object is placed on the target.	Reinforces the movement goal, trajectory and speed, depending on the choice of AF.
Luminescence/Aura effect for proximity to target	
As the object approaches the correct target, a waxing 'aura' appears around the target.	Communicates correct movement choices and accuracy.

target area. Thus, 100% would mean perfect overlap. Movement speed is given by the rate of object movement during task performance and is measured in m s^{-1}. Accordingly, improvement on this variable would be denoted by increased scores. Movement efficiency is the deviation from the straight-line path between targets (this metric was included since research indicates that non-disabled persons typically move in straight lines during upper-limb transport movements, see [32] for discussion). This variable is measured as a percentage score: (total straight-line distance between the sequence of targets/distance moved) × 100. In addition to training, Tasks 1 and 3 were used as assessment tasks (administered without AF to minimize practice effects). Furthermore, since research has indicated that movement speed and accuracy are related variables (i.e. one can be improved by sacrificing the other [22]), it is important that performances on these variables are considered together.

Standardized measures of functional skill

Upper limb function was also assessed using two standardized measures. These assessments were included to give an indication of the functional improvements participants made, since they both have good predictive validity. The presentation order of the assessments was counterbalanced, ensuring participants did not perform them in the same order in two consecutive sessions.

Box and Block Test (BBT)

The BBT consists of two connected boxes (each 27 cm × 24 cm, with walls 8.5 cm high), separated by a vertical wooden barrier (15.2 cm high). One box is filled with 150 2.5 cm wooden cubes. The goal is to move as many blocks as possible, one at a time, in 60 seconds using one hand. The BBT has excellent test–re-test reliability and predictive validity and has been used frequently among TBI populations [33].

McCarron Assessment of Neuromuscular Dysfunction (MAND). Research has indicated that unilateral upper limb training can improve bi-manual co-ordination [34]. Thus, two tasks assessing bimanual dexterity from the MAND test battery were used in this study. For the nuts-and-bolts tasks, participants hold a metal nut in their non-preferred hand and screw either a large or small bolt into the nut as quickly as possible with their preferred hand, with no upper time limit for the task. The bead-threading task requires participants to hold a metal rod in their non-preferred hand and thread as many wooden beads as possible onto it in 30 seconds. These MAND tasks have also demonstrated good individual reliability and validity and are recommended for use among neurologically disabled populations, including TBI [35].

Procedure

Design of case studies. Case studies assess the effect of a treatment by comparing change in the dependent variable(s) for a single participant under varying treatment conditions (typically baseline and treatment phases) [15]. Accordingly, unlike a between-groups study with a separate control group, case studies utilize a repeated-measures approach, where the baseline data for each participant serves as the control data to be contrasted against their treatment phase performance (see [36] for further discussion on case study design). An ABA time-sequence design with multiple baselines between participants was used here. The first baseline phase (A1) consisted of an initial series of assessments of upper-limb function (VR-system variables; accuracy, speed, efficiency and standardized measures; BBT, MAND tasks). This phase lasted four sessions for TJ, seven for SK and nine for AN. The length of the A1 phase was based on recommendations of at least three-to-four data points in the baseline phase [36]. Accordingly, A1 lengths of four, seven and nine were sufficient to establish the participants' baseline performance. Moreover, the multiple-baseline between subjects design requires varying baseline times between participants to gauge if a temporal relationship between the initiation of treatment and improved performance occurs [37]. In this study the A1 lengths represent participants' level of recovery, with TJ (the most recovered) requiring a shorter A1 time to establish his performance level, then SK had the second longest (seven sessions) and finally AN had nine sessions.

The intervention phase (B) was comprised of 12 60-minute sessions, conducted over a 4-week period. This structure for treatment is consistent with recommendations for patients with TBI [38]. Performance was assessed at the conclusion of each session. Following the B phase a second baseline (A2) was conducted. The purpose of the A2 phase was to assess whether any improvements participants made during the B phase persisted after they stopped using the training. This phase consisted of five sessions for TJ and AN and six for SK (the A2 phase was intended to be six sessions for each participant, however TJ and AN were absent for one session).

All testing was conducted onsite at the Epworth hospital. For each intervention session participants performed the four tasks using AF. The aim was to improve their level of performance across the three system-measured movement variables (accuracy, speed and efficiency) and the participants had end-point and weekly goals for each.

Treatment administration. The exact number of tasks performed per session varied a little due to situational factors like the participant arriving late for a session or needing to use the bathroom, and so on. However, each of the four tasks was administered an equal number of times per session and each arm was tested.

Participants were also shown performance graphs that depicted their accuracy, speed and efficiency by session (the raw data plots later used in the data analysis). The aim here was to motivate the participants by keeping them informed of their progress over time. As well, one was able to compare accuracy, speed and efficiency variables and adjust performance priorities accordingly. Thus, participants spent ~40 minutes of their session performing the four tasks with AF, then their performance graphs were reviewed and the last 5–10 minutes of the sessions were used for assessment administration.

Data analysis. The data analysis is comprised of two levels: (i) visual inspection of exponential data smoothing (EDS) time-series plots and (ii) statistical analysis (either two-standard deviation (2SD) band analysis or Split Middle Trend Analysis (SMTA)). EDS was used to minimize the variability and random fluctuations in the data and highlight performance trends, allowing more reliable sight inspection [39]. This data smoothing procedure is considered superior to other methods (such as simple moving average smoothing) since more recently observed data points are given more statistical weight in calculating smoothed values. Accordingly, the weight put on the previous observed data points during the calculation is determined by the α value used in the EDS formula (between 0–1, see [39]), with larger α values assigning greater weight to more recent observations. The α value used in calculating each EDS set results in the smallest difference between the smoothed data points and the actual values [39].

The EDS results were presented as time-sequence graphs and sight inspected to assess changes between the A1 and B phases. Then, scores from the B and A2 phases were compared to determine whether intervention phase performance was maintained. It should be noted that instances of missing data are represented by a gap in the time-sequence plot.

To complement sight inspection statistical analyses were used to contrast the A1 and B phase data. Two-standard deviation (2SD) band analyses were performed on variables with a stable baseline. This statistical method is based on the mean and SD of the baseline data. If at least two consecutive data points from the B phase fall above (or below depending on the index of improvement) the two SD range, a significant ($\alpha < 0.05$) change in performance has occurred [40, 41]. However, 2 SD band results may be misleading if the baseline shows a marked trend [40]. Accordingly, for variables where baseline scores showed a distinct trend, SMTA was used. SMTA projects a celeration (or 'best-fit') line from the A1 phase to the B phase of a time-sequence graph. Cumulative binomial analyses then assess whether a significant number of data points are above or below the celeration line in the B phase [40]; binomial tests used a probability of 0.5 and significance of $\alpha < 0.05$.

Results

System-measured variables

Accuracy. The time-sequence plots for accuracy are presented in Figure 2. Sight inspection of these

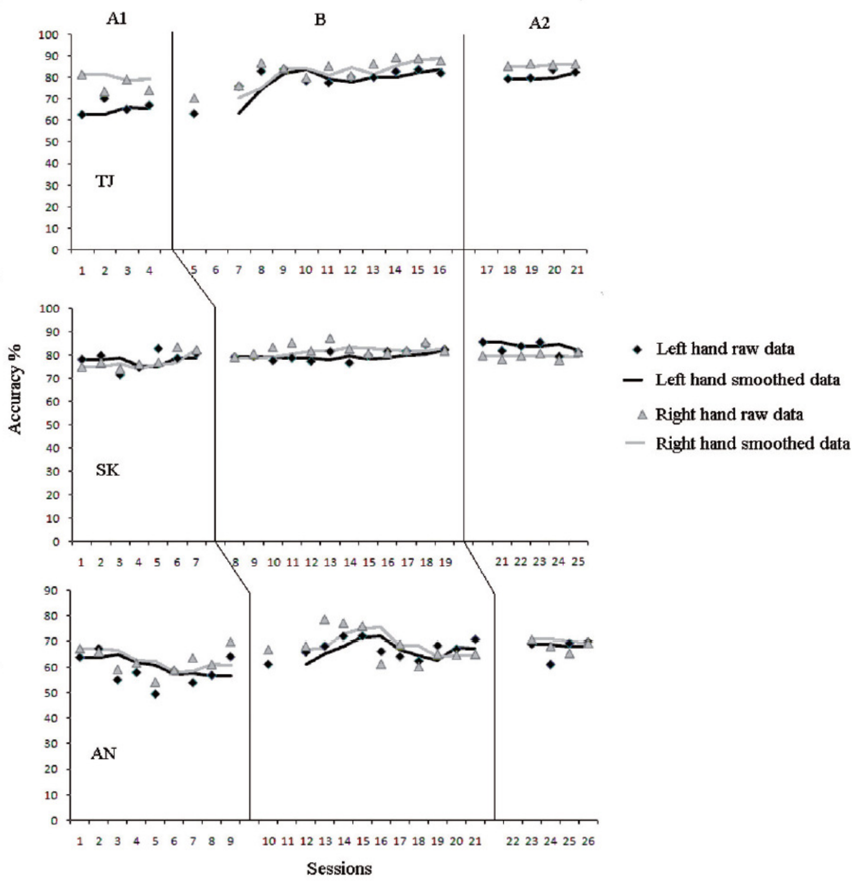

Figure 2. Time-sequence plots for movement accuracy all participants.

graphs indicated improvements for both hands for participants TJ and AN between the A1 and B phases. These improvements were maintained into the A2 phase. SK demonstrated no improvement on his left hand and the moderate improvement that was evident for his right hand in the later treatment sessions was not maintained into A2. Follow-up 2SD band analyses indicated significant improvements for participants TJ (baseline right hand $M(\mathrm{A1}) = 77.05$, $\mathrm{SD} = 3.83$; left hand $M(\mathrm{A1}) = 66.56$, $\mathrm{SD} = 3.16$) and AN (baseline right hand $M(\mathrm{A1}) = 62.22$, $\mathrm{SD} = 4.88$; left hand $M(\mathrm{A1}) = 58.40$, $\mathrm{SD} = 5.64$).

Speed. TJ, SK and AN demonstrated no improvements in speed for either hand. However, despite a drop off in speed for TJ in the B phase and to a lesser extent SK (right hand), their performance variability was far less through the A2 phase; indeed, there was some improvement evident for SK's left hand during A2. Statistical analyses confirmed no significant improvements in speed for any participant.

Efficiency. Sight inspection of the smoothed efficiency data indicated improved performance between A1 and B phases for participant TJ's left hand, SK's left and right hands and AN's right hand. These improvements were maintained into the A2 phase. For participant TJ, this (moderate) improvement occurred towards the end of the B phase with both hands, whereas SK and AN's performance improved at the beginning of the B phase. Significant results from 2 SD analyses were found only for SK's right hand ($M(\mathrm{A1}) = 83.16, \mathrm{SD} = 4.44$), and AN's right hand ($M(\mathrm{A1}) = 85.54, \mathrm{SD} = 2.27$).

Standardized measures

BBT. Sight inspection indicated that TJ and SK moved more blocks with their left and right hands in the B phase compared to A1 and maintained that improvement into A2. AN demonstrated improvement in the B phase for his left hand only, which was maintained into A2 (see Figure 3). However, given the clear upward trends in some baseline performances on this test, SMTAs were performed. These showed that the improvements between baseline and treatment were not significant for TJ's right hand ($n = 12, p = 0.99$) or SK's left hand ($n = 12, p = 0.999$). Significant improvements were found in 2 SD band analyses for TJ's left hand ($M(\mathrm{A1}) = 51.25, \mathrm{SD} = 3.4$), SK's right hand ($M(\mathrm{A1}) = 39.71, \mathrm{SD} = 3.04$) and AN's left hand ($M(\mathrm{A1}) = 28.11, \mathrm{SD} = 1.45$).

MAND. The time-sequence plots for the MAND tasks showed mixed results. For the nuts-and-bolts task, marginal improvements (reduced time to complete the task) were seen for TJ on both versions of the task. TJ's improvement for the small bolt task was maintained into the A2 phase, however he tended to take longer with the large bolt in the A2

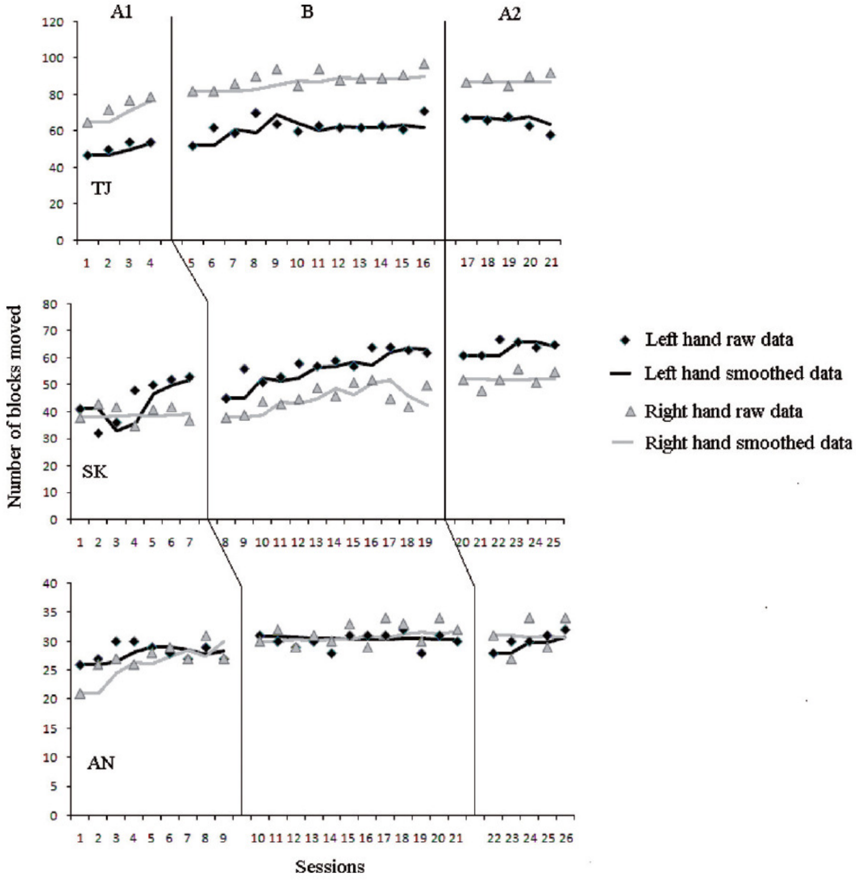

Figure 3. Time-sequence plots for the box and block test for all participants.

phase than either of the previous phases. Participant SK showed improvement toward the end of the B phase for both tasks, which continued into the A2 phase. AN showed no reduction in time for either task during or after treatment. Significant improvements were confirmed by 2 SD band analyses for participant TJ on the large version only ($M(\mathrm{A1}) = 17.18, \mathrm{SD} = 1.37$).

For the bead threading task, some improvements in performance were visible for participants TJ and SK in the B phase and A2 scores increased compared with baseline levels. AN did not demonstrate improved performance during the B phase. However, AN's A2 scores were less variable and exceeded those from the previous two phases. Accordingly, 2 SD band analysis indicated significant improvements for TJ ($M(\mathrm{A1}) = 13.67, \mathrm{SD} = 0.58$) and SK ($M(\mathrm{A1}) = 9.43, \mathrm{SD} = 0.79$).

Discussion

The aim of the present study was to evaluate the effectiveness of a new VR-based system for upper-limb rehabilitation in individuals with TBI. The case study results generally support the efficacy of the system at two levels: system-measured performance and functional skill. Using multiple baselines across participants, a relationship was shown between the timing of the treatment and levels of performance for several variables. These treatment effects were evident despite all participants continuing conventional therapy and were largely maintained at A2. Performance trends are discussed in more detail below.

System-measured variables

At the beginning of the study, TJ's hand function was generally well rehabilitated. He scored highly on the speed and efficiency variables but his accuracy scores were relatively low at baseline. Therefore, his goal was to improve accuracy while maintaining acceptable speed and efficiency. This objective was achieved despite an initial decline in speed early in treatment. Overall, his pattern of change suggests improvement in motor control, mirrored by improved efficiency (though not statistically significant). TJ's results in the B phase were also maintained at A2, indicative of motor learning.

Participant SK's progress on the system-measured assessments were the most variable. He appeared to take longer to engage with the therapy, which may have explained his relatively late improvement in accuracy compared to AN and TJ. Nonetheless, SK demonstrated the most notable improvement on efficiency. This suggests that trace AF may have been used preferentially to assist in his movement planning. SK commented on how he could 'imagine the trace' during the assessment tasks (where no AF was present) to help guide his movement path. In sum, SK's efficiency results tend to support the theory that AF provided in a graded series of VEs can result in improvements in motor control.

Participant AN showed significant improvement on both left and right hand for accuracy. During baseline and the start of the intervention AN's movement of the object during transport was fast, but his terminal control was less developed, causing poor accuracy scores (50–60% during the A1 phase). His accuracy toward the end of training was ~70%, with no decline in speed. This finding indicates genuine improvements in motor control. Based on Fitts' Law [22], one might expect improvement on one of these variables at the expense of the other, but this was not the case. AN also improved significantly on efficiency for his right hand, suggesting his overall movement patterns became smoother. Maintenance of these improvements into the A2 phase again suggests stability in the organization of movement patterns. Notably, participants tended to focus on improving their accuracy, since this was the most obvious deficit during baseline. A different pattern of change may result in other cases where speed or efficiency are targeted for improvement, based on initial performance.

Standardized measures of functional skill

Participant TJ showed improvements on the (large) nuts-and-bolts test, the beads task and BBT (left hand). For the large nuts-and-bolts test, TJ's slower performance during A2 indicates that, while he was able to improve his bimanual movements, he reverted to an earlier movement pattern during A2. SK's right hand BBT results and beads tasks all showed significant treatment effects; so too did AN's left hand BBT results. Taken together, these findings support the efficacy of the Elements system in training aspects of object manipulation and control, since improvements were noted for each participant. However, because not all changes were statistically significant, a longer course of VR therapy may be needed to consolidate improvements in functional skills.

The absence of significant improvements on the small nut-and-bolt task indicates that the course of training had only minor effect on more fine-grained control of the fingers. However, these results may mask a general training effect. It is possible that fine manipulative skills were undergoing a period of re-organization due to intervention, but new movement patterns were not yet established [23]. Further research with a longer training schedule is needed to investigate these more subtle learning effects.

General discussion

Findings here demonstrate that providing AF using a series of graded tasks in a VE can facilitate motor learning in TBI, and are consistent with other (non-VR) AF research [26, 27, 42–44].

The system's AF was designed to help participants focus their attention on the external effects of their movement—a commonly used practice in sport science and training [31]. Research on normative and TBI populations has demonstrated that development of motor skills progresses from slow, consciously controlled movements to more rapid, autonomous action [45, 46]. During this progression, the performer's attention shifts from internal to external focus (i.e. toward the effects of their movement rather than its biomechanics). Participants with TBI often find the transition to so-called automatic control as difficult. This study argues that by prompting participants to focus their attention externally, the transition may be enhanced [31]. However, the precise nature of this effect is in need of further research.

The Elements task environment placed progressive demands on motor planning, while maintaining a common set of movement goals. The cognitive deficits associated with TBI underpin their difficulties in motor planning [47]. Based on ecological approaches to movement (with interacting *individual*, *task* and *environmental* constraints [22]), it is argued that the performance effects observed were due to cognitive change at the level of movement planning. These improvements were facilitated by scaling the difficulty of the training tasks and provision of AF. The latter reinforced the performer's knowledge of the relationship between their movement command signals and their resultant effects on the body. This knowledge is at the heart of predictive control: AF of the type provided here is regarded as a means of training internal modelling [22].

Another important aspect of the training package was the use of performance graphs. It was observed that this process enhanced motivation for therapy, which is a vital part of training [48]. This type of feedback is thought to improve participants' motivation by promoting self-efficacy and overall well-being [48]. While assessment of these psychological outcomes was beyond the scope of the present study, it was observed that patients showed great interest and pleasure in their graphs. Thus, these participants received AF and performance graph feedback each session. It is contended that this feedback schedule was an effective means of enhancing their sense of self-efficacy and psychological well-being. The effect of different schedules of feedback is an issue for future research; for example, the use of continuous vs summary feedback using graphs.

As VR rehabilitation progresses, researchers will need to tease out the particular aspects of training and other factors that best predict change—for example, the effect of chronicity on treatment effects. This study noted less improvement on several variables for participant SK (e.g. accuracy) whose TBI occurred more recently than AN or TJ.

Those measures that showed mixed training effects generally involved some form of bimanual coordination, for example MAND sub-tests. This finding has also been shown in earlier research [34]. Hence, a role for the development of VEs that target bimanual coordination was seen; one would predict greater improvements on the MAND tasks given an adequate course of therapy. One possibility is incorporating multiple objects into the tasks and then setting up affordances for coupled or sequential actions (see [49, 50] for discussion on the use of bimanual activities in rehabilitation). Another option is varying the size and shape of objects to promote different grasps and modes of prehension.

Additionally, the Elements tasks involve a single plane of movement, whereas many upper-limb activities use multiple planes. Virtual workspaces that encourage the latter may increase the generalizability of the training. However, the challenge remains to create these VEs using current, low cost technologies. Despite these limitations, the results obtained on standardized measures are consistent with VR studies involving stroke patients [28, 51–55]. One important area for future investigation concerns whether time since injury and injury severity are factors in VR-rehabilitation (as in traditional therapy [56]). A larger sample comparison is planned to address these issues.

Conclusion

This study demonstrates that a new, low cost VR system shows promise in improving upper-limb function in patients with TBI, although gains were not evident on all measures. The Elements system presents a series of tasks that make progressive demands on motor planning and provides users with real-time AF related to their movement. The VR-based technology enabled one to harness these factors in promoting aspects of motor control. Although not all results were significant, many still showed positive trends from visual inspection.

It should also be reiterated that the Elements system is intended to complement traditional rehabilitation. It is believed that designing VR systems in such a way that they can be used in conjunction with established therapies is crucial to their success. Indeed, systems that have been designed to replace *in-vivo* training have often been shown to be impractical during development and usability trials [57, 58]. Moreover, the effects of VR alone does not generally exceed that of traditional methods [59, 60]. Taken together, data presented here provide some optimism that VR can be integrated into a comprehensive rehabilitation framework. The extent to which VR can value add to traditional procedures will ultimately determine whether it will become a more standard practice in the future.

Acknowledgements

This work was supported in part by an Australian Research Council (ARC) Linkage Grant LP0562622, and Synapse Grant awarded by the Australia Council for the Arts. We wish to acknowledge the contributions of other members of the broader Elements project; Ross Eldridge and Dr Heiko Rudolph from the School of Electrical and Computer Engineering, RMIT University, and Mark Guglielmetti, an artist and Lecturer with the School of Art and Design, Monash University.

Declaration of Interest: The authors have no conflict of interest with respect to the development and validation of the Elements system.

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