Virtual reality environments for rehabilitation of perceptual-motor disorders following stroke

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ABSTRACT

The incidence of perceptual-motor disorders arising from stroke is steadily increasing in the population of Europe and the USA. This paper outlines the potential role that virtual environments (VE) may play in designing remedial programmes for rehabilitation following stroke. Key principles for the structure of guided learning are identified, but emphasis is also placed on the need to identify when, and how, VE technology can introduce added *value* to the therapy situation.

Keywords: virtual reality, stroke, hemiparesis, rehabilitation

1. INTRODUCTION

To some degree Virtual Reality (VR) has been a technology in search of an application. Central components of the genesis of VR such as the head-mounted displays and dataglove were the result of scientists such as Sutherland (1968) exploring what was technically feasible, rather than from a specific application where computer users needed stereoscopic depth or complex manual interaction. Recently, much has been made of the potential for the use of VR in medical contexts. In general the attention and speculation has been concerned with either remote or augmented surgery, and surgical training. Because many surgical procedures are still critically dependent upon the co-ordination between eye and hand, this is an ideal application for a technology that seeks to provide a reconstruction of visual and haptic arrays and allow direct manipulation. Reciprocally, the precision required in surgical interaction also sets it as a critical test of the extent to which VR systems can adequately simulate natural interactions. Another potential use of VR in the medical industry that has received less attention is rehabilitation and treatment. Although surgery and therapy are both seen as worthy candidates for high-cost computer simulation, there is an important distinction to be made about the information that it is necessary to provide through such simulations. As discussed above, a central component of tele-operation or surgical training is transmitting information to the user that closely approximates the information they would use in a natural setting; so the stereoscopic depth of the patients organs should be appropriately scaled and the users head and hand movements should result in appropriate spatio-temporal changes in the display. The goal of therapy, however, need not be the recreation of "reality". If the goal of VR is to enhance the therapeutic context there is little point in recreating the natural environment that the patient has access to. It may be effective to recreate aspects of the natural environment that a patient has lost access to (e.g. simulated motion) or to transpose a particularly salient source of information to a context in which it would not normally arise (see section on hemiparesis). In this respect that task is not the recreation of "reality" but the recreation of a therapeutic environment, hence we will use the term virtual environment (VE) in the discussion that follows.

Parkinson's Disease has provided an initial focus for the use of VE augmentation (Prothero, 1993). The ability of akinesic patients breakout of a frozen posture and locomote when presented with stepping stone targets is well documented. Prothero (1993) presented Parkinson's patients with virtual stepping stones via a head-up display to enable patients to maintain gait. It was also reported that one patient was then able to spontaneously locomote even without virtual targets. The latter finding is promising but not unusual. There are a number of strategies that arise from the anecdotal reports that Parkinson's patients can use to initiate locomotion (e.g. music and dancing), but they are also invariably transient in their effectiveness. It would be overly ambitious to suggest that VE might have lasting therapeutic value for patients with progressive biochemical disorders such as Parkinson's disease. It may be able to

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ameliorate specific deficits or stimulate the discovery of coping strategies, but ultimately it is unlikely to stimulate the natural production of dopamine. There are therapeutic areas, however, where *information* may hold the key to rapid improvement. This paper suggests two examples where the common thread is the need to direct attention. In the case of an attention deficit such as unilateral neglect there is a specific difficulty in focusing attention, where as in hemiparesis it is suggested that a sharpening of the focus may accelerate the re-acquisition of neuromuscular control. In all cases VE may provide a spotlight for the direction of attention.

2. UNILATERAL NEGLECT

A significant percentage of individuals who suffer a stroke, subsequently present with unilateral neglect. This is manifest in an apparent disregard of visual space contra-lateral to the lesion. In many cases reduction of neglect is evident during the first 12 weeks post-CVA. In a small number of cases, however, neglect is experienced as a longer term problem. Classic symptoms of neglect include shaving only one side of the face and eating the food on just one side of the plate. Clinical indicators that have been used are errors in bisecting lines, letter cancellation and figure copying, where an ipsi-lateral bias is generally evident. Neglect may be observed in the absence of visual field deficits and may be manifest in the extinction phenomena in which a visual feature on the contra-lesional side that was previously visible "disappears" when a similar object is presented in the ipsi-lateral visual field. A complementary paper in these proceedings (Rushton, Coles & Wann, 1996) provides a detailed background to existing therapy and the potential of virtual environments. The essence, however, is to capitalise upon the potential of VEs to provide attentional cueing through stimuli that may vary in colour, size, motion and depth. The plasticity of the virtual visual environment allows the tailoring of stimuli to provide greater precision in assessment procedures and a greater variety of therapeutic tasks.

3. HEMIPARESIS

Although unilateral neglect is not evident in all patients following stroke the majority will experience some degree of lateral paralysis, manifest in the loss of muscular control and the impairment of muscular sensation for the contra-lesional side. Hemiparesis will often affect the facial musculature, lower limb and upper-limb, particularly the distal extremities such as the fingers. Recovery can occur quite rapidly over the first 3 months (Fugl-Meyer, 1975; Wing et al, 1990), but thereafter may follow a negatively accelerating curve reaching a plateau below full function. Typically, there may be considerable recovery for proximal musculature such as postural control and relatively poor control attained for hand and finger control or for control of the contra-lesional foot. A primary goal of therapy is to enhance acquisition, particularly during the latter stages of recovery and avoid the early plateauing of active function. The most effective means of achieving such enhancement is open to debate.

Most conventional physical therapies that are used in the treatment of motor pathologies have evolved over considerable periods of innovation and refinement. The effects of conventional therapy for a number of motor disorders, however, are unclear. Despite the convictions of therapists, formal assessments of the efficacy of therapy for disorders such as congenital cerebral palsy have been inconclusive, (Tirosh and Rabino, 1989; Turnbull, 1993). It is not suggested that therapy is futile, quite the contrary, but the goals need to be continually reviewed in the light of current research on motor control and rehabilitation. It is also the case that therapists are severely restricted in the information or stimulation that can be provided to the learner (patient). This position paper considers what a current research in motor control suggests should be the primary goals of motor therapy and proposes a project for the development of tools that would enable a major step in the technological support for therapy

3.1 A Movement Perspective for Therapy

The bulk of research into human motor control has followed the lead of early researchers such as Woodworth (1899) and Lashley (1917) and focused on the efferent and afferent contributions in muscular control. The primary focus has been on the individual's musculo-skeletal system, the patterns of movement produced and neural control of such movements. Furthermore, a common theme across such an approach has been the requirement of some neural representation of the movement to be performed, either in the form of an error comparator for sensory feedback, a program of commands, or schema for generation of a generalizable response and expected sensory consequences. Although there has been substantial disagreement about the precise form that such a representation might take, the process of skill learning from a movement perspective requires that the individual learns about the capabilities and constraints of their motor system. There are hypotheses which avoid the inception of an explicit program, but these do not negate the need to "learn about one's system". Mass-spring models of aimed limb movements (Feldman, 1966, Bizzi 1980) suggested that a limb positioning could be achieved purely by specifying movement endpoints and that movement kinematics can be realised by exploiting the spring-like properties of skeletal muscle. But even this very simple spring-to-end-point model of limb movement requires some implicit knowledge and effective tuning of limb

impedance to control trajectory speed and stability . It must be stressed that the acquisition of such knowledge may not be explicit, an individual will seldom "know" the precise configuration of their upper-limb musculature. But our everyday actions where we deftly reach and pick up fragile objects indicates that the control system has implicit knowledge of the dynamic characteristics of the upper-limb. Conversely, the attempts of an individual with spastic quadriplegia to complete the similar tasks highlights that there are problems in the interface between desired action and resultant movement. Computational algorithms for implicit learning of motor characteristics have been made presented by Jordon (1990) who proposed the learning of forward and inverse models of a hypothetical motor system. In simple terms the naive actor uses early explorative behaviour to build a model of the effects that a given set of commands will have in terms of the limb and environment (*forward model*). This is then used to form the *inverse model* of what commands are required to yield a specific desired effect. What can be gleaned from this perspective that would provide some principles for therapy with severe movement pathologies? In the case of hypertonicity or hypotonicity, it is obvious that the dynamic properties (stiffness, muscular recruitment, response characteristics) of the affected limbs are profoundly altered (Brown et al, 1987). Where changes occur following misadventure then it is clear that therapy must allow the individual to progress through a re-education or re-exploration of their motor system.

The focus of the movement perspective, described above, has been criticised as being overly prescriptive. An *action* perspective stresses that an animal's capabilities can only be understood in relation to the environment in which it acts. One should not focus purely on the movements of the body, but rather on how the union between the animal and its environmental *niche* unfolds. A predominant theme in the action perspective is the identification of the *affordances* (potential action) that the environment offers the animal (Gibson, 1979) and how these may be capitalised upon to yield skilled behaviour. The problem with translating this perspective to therapy is that the research effort has been predominantly elitist. Researchers have focused on highly skilled performers such as gannets (Lee & Reddish, 1981), long-jumpers (Lee et al 1982) and jugglers (Beek, 1989). Very little research has focused upon animals/humans who fail to mesh with their environmental niche. The main contribution from the action perspective would seem an emphasis on the role of functional, exploratory interaction between the actor and the environment.

An illustrative example of this point can be found in Conductive Education which stresses goal orientation for the child and that "dysfunction is not a property of the child, but the product of the interaction between himself, or the way he is, and his environment" (Hari & Tillemans, 1984,; p. 27). Hence the focus is on ortho-function and the child actively solving tasks in a way that is most appropriate for him/her. This contrasts sharply with traditional approaches such as Bobath (1973) who proposed the principles of therapy to be the suppression of abnormal reflex activity and facilitation of normal righting and that the CNS could be substantially changed by taking the child passively through postural patterns that conflicted with the abnormal reflex response.

3.2 Principles for action based therapy

1. Provide a therapeutic environment that highlights the consequences a patients actions to allow them to identify the (changed) characteristics of their system (*Movement Principle: forward modelling*)

2. Provide a setting where they can try and test adaptive movement strategies (*Movement Principle: inverse modelling*).

3. Present the patients with functionally related tasks that have clear goals rather than prescribe movement sequences or patterns of contraction *(Action principle 1)*.

4. Allow the patient to explore the environment and arrive at solution to his/her specific movement problems, rather than guide them through constrained routines *(Action principle 2)..*

3.3 The virtual learning environment: Identifying "added value"

When considering how a VE can enhance the therapeutic setting one might proposed that it can be used to provide the patient with a virtual body or limb. This avenue does have a number of limitations that require consideration. A patient with hemiparesis has lost the ability to produce sustained contractions of the limb musculature. Over time there is often some recovery of this ability, particularly for the proximal musculature. The re-acquisition of skill may in part be due to simple post-trauma effects, but is also likely to require some degree of neural re-organisation and recruitment in the light of impaired transmission through the cortico-spinal tract. What role would a virtual limb have in guiding the re-acquisition of skill? If the patient is unable to move their natural limb is their any value in providing them with an image of a virtual limb? There would appear to be some potential for this paradigm, but there are constraints to be considered. A virtual limb may be presented as a model for the patients action: Using a see-though head-mounted display, it is viable to present the patient with a virtual limb superimposed in a location close to their own limb. The virtual limb may be moved computationally as a tracking task for the patient to mimic the range and speed of motion. Despite the attraction of the technology, there is no formal basis to presume that this paradigm would be any more effective than presenting the patient with a series of real tasks, such as pushing blocks and wiping tables, that are

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common in conventional occupational therapy. To justify the use of VE technology there is a need to identify *added value*, where the therapeutic paradigm provides a stimulus that is not available in the natural therapy setting. We may justify the virtual-arm paradigm by making recourse to the early stages of post CVA recovery where the patient may have very little overt movement of a limb. The patient in the early stages of recovery may be able to initiate EMG activity, but the motor unit recruitment is insufficient to overcome the inertia of the limb and produce a change of limb position. A virtual limb, however, may then be a useful and stimulating way of encouraging specific patterns of recruitment. Biceps and triceps EMG can be taken as the peripheral inputs for motion of the virtual limb, such that a rise in triceps EMG, in the absence of biceps EMG produces extension of the virtual limb around the elbow, whereas a reciprocal pattern produces limb flexion. Co-activation of both EMG inputs produces slowing of the limb and eventually virtual-rigidity. Hence the patient who is unable to produce overt limb movement can be presented with a task in which their goal is to re-learn simple patterns of motor unit recruitment, building towards the tri-phasic EMG pattern that is the hallmark of skilled upper-limb movements. This latter example exploits *Principle 1:&2* to provide the patient with *information* that may not otherwise be available to them (e.g. how they are actually contracting their musculature) that may allow them to identify suitable strategies.

   This therapeutic approach is somewhat similar to conventional biofeedback therapy. In biofeedback a patient would typically be provided with a specific movement goal, such as the regulation of activity in a specific muscle group. Augmented sensory cues would be provided in the form of vision (of an oscilloscope trace) or sound that reflected the electrical activity monitored from the muscle group. The subject's goal would be to find a control strategy that produced the correct augmented sensory feedback. This could be considered as a simplified case of forward-inverse system modelling, or could equally be considered as little more than operant conditioning. The issue is what can the individual "learn" that is transferable to functional activities ? A number of studies have demonstrated short term gains with biofeedback training of discrete muscle groups (Mroczek et al, 1978; Middaugh & Miller, 1980; Nemec & Cohen, 1984; Mulder et al, 1986), hence augmented feedback can clearly enable subjects with motor pathologies to gain greater control over skeletal muscular responses. There is little evidence, however, that such gains are long-term or that this control can be transferred outside the training context. The stumbling block of conventional biofeedback is that the regulation of contraction in a single muscle group, or even a collection of muscles is far removed from functional goals. The use of VE systems in a traditional biofeedback mode (e.g. Warner & Jacobson, 1992) may provide a useful stimulus to early exploration or provide the patient with a useful computer interface, but falls well short of functional rehabilitation (Wann & Turnbull, 1993).

3.4 Fashioning the learning environment: Providing action feedback

Rather than providing feedback about the patient's biological or muscular-function it is proposed that greater gains may be possible if the environment enhances and highlights the consequences of the patient's action, rather than reflecting aspects of their motor control. In pathology naturally occurring cues, such as proprioception, may often be unreliable or have lost their salience. What is required is augmented feedback that can be fashioned to match the individuals capabilities and prompt the individual towards finding unique solutions to movement problems. Physical laws impose constraints on the manipulation of naturalistic settings. It is difficult to slow down a falling ball to allow a child more time to organise his/her movements, or to stop water from spilling when a cup is moved jerkily towards the mouth. VE technology, however, can provide an interactive environment tailored to the needs and abilities of the patient. Restricted powers of movement and manipulation need not set limits upon the quality of interaction. The mapping between limb movement and movement in the VE is arbitrary, the input from a limb can lose its tremor, through low-pass filtering, or a single finger movement can control virtual locomotion. This flexibility allows the augmentation or amplification of sensory feedback to a perceptual system that may have lost some degree of its natural sensitivity. As the content of a VE can be directly specified, the patient may be given progressively more complex and rich environments. Distracting objects can be banished and the laws of physics bent or relaxed. Simple training tasks can be set in a meaningful context thus developing skills that are immediately useful to the patient, thereby enhancing the patient's sense of accomplishment and engendering future interaction. Without moving from the treatment room the patient can experience information rich environments without the inconvenience often associated with complex natural settings.

4. A POSITION STATEMENT

Virtual environments provide the potential to computationally specify the visual and auditory environment that is presented to an observer. This opens up interesting new avenues for exploring human skill acquisition (Wann *&* Rushton, 1995a,b; Wann et al 1995), but also presents possibilities for guided learning in a remedial setting (Wann & Turnbull, 1993; Kuhle & Dohle, 1995). This paper identified 4 principles for the design of therapeutic environments that arise from existing work on perceptual-motor learning. There is a clear potential for virtual environments in meeting those goals in a manner that is not possible within the constraints of a natural therapy setting. The power of the VE setting is the ability to selectively tune the environment to provide specific patient goals and the ability to provide real-time feedback with tuneable input-output gains. The principle benefits of the VE environment in a therapy setting are:

i) A 3-D virtual environment can "immerse" the patient to the degree that they will demonstrate appropriate limb & postural corrections in response to virtual environmental (VE) perturbations.

ii) The illusion of (i) coupled with the patients ability to directly manipulate the VE display will produce a considerably stronger learning environment than conventional therapy approaches

iii) The ability of the patient to explore, interact and make errors in the VE environment will provide a facility for motor re-learning unparalleled outside of a VE setting.

iv) The novelty and intrinsic appeal of such an interaction will also provide a powerful motivation factor for rehabilitative exercise.

It is important, however, that the potential of VR is not squandered by "throwing" VE technology at the problem without a formal appraisal of where and how it may provide *added value*. The rehabilitation communities have traditionally welcomed interest from technology providers and therapists are often interested in the potential role that computing or sensor technology may have remedial programs. That goodwill may be lost if virtual reality applications are not clearly focused to capitalise upon the existing knowledge base in motor control and rehabilitation.

5. REFERENCES

Beek PJ (1989) *Juggling Dynamics*. PhD Thesis, Free Univ, Amsterdam: Free University Press.

Bizzi E (1980) Central and peripheral mechanisms in motor control. In Stelmach GE & Requin J (Eds.) *Tutorials in Motor Behavior*. Amsterdam: North Holland

Bobath K (1980) *A Neurophysiological Basis for the Treatment of Cerebral Palsy*. Spastics International Medical, London: Heineman

Brown JK, van Rensburg F, Walsh G, Lakie M & Wright GW (1987) A Neurological study of hand function of hemiplegic children. *Developmental Medicine & Child Neurology* 29, 287-304.

Feldman AG (1966) Functional tuning of the nervous system with control of movement or maintenance of a steady posture. II Controllable parameters of muscle. *Biophysics* 11, 565-578.

Fugl-Meyer AR, Jaasko L., Leyman I., Olsson S. & Steglind S. (1975) The post-stroke hemiplegic patient: I, A method for evaluation of physical performance. *Scand. J. of Rehabilitation Medicine* 7, 13-31.

Gibson JJ (1979) *The Ecological Approach to Visual Perception*. Boston: Houghton-Mifflin.

Hari M & Tillemans T (1984) Conductive Education. In Scrutton D (Ed) *Management of Motor Disorders of Children with Cerebral Palsy*. Spastics International Medical, Oxford: Blackwells.

Jordon MI (1990) Motor learning and the degrees of freedom problem. In Jeannerod M (Ed.) *Attention & Performance* XIII, pp 796-836. Hillsdale NJ : Lawrence Erlbaum.

Kuhlen, T & Dohle, C. (1992) Virtual reality for physically disabled people. *Comput. Biol. Med.* 25, 205-211.

Lashley KS (1917) The accuracy of movement in the absence of excitation from the moving organ. *Am. J. of Physiology* 43, 169-194.

Lee DN, Lishman JR & Thompson J (1982) Regulation of gait in long-jumping. *Journal of Experimental Psychology: Human Perception & Performance* 8, 448-459.

Lee DN & Reddish PE (1981) Plummeting gannets: a paradigm of ecological optics. *Nature* 293, 293-294.

Middaugh SJ & Miller MC (1980) Electromyographic feedback: effect on voluntary muscle contractions in paretic subjects. *Arch Phys Med Rehabil* 61, 24-29

Mroczek N, Halpern D & McHugh R (1978) Electromyographic feedback and physical therapy for neuromuscular retraining in hemiplegia. *Arch Phys Med Rehabil* 59, 258-267.

Mulder T, Hulstijn W & van der Meer JPT (1986) EMG feedback and the restoration of motor control. *American Journal of Physical Medicine* 65, 173-188.

Nemec RE & Cohen K (1984) EMG biofeedback in the modification of hypertonia in spastic dysarthria. Arch Phys Med Rehabil 65, 103-104.

Rushton S., Coles K.L. and Wann, J. (1996). Virtual Reality technology in the assessment and rehabilitation of unilateral visual neglects. *Proc. ECDVRAT.* Reading UK, July 1996.

Seeger BR & Caudrey DJ (1983) Biofeedback therapy to achieve symmetrical gait in children with hemiplegic cerebral palsy: Long-term efficacy. *Arch Phys Med Rehabil* 64, 160-162

Sutherland I.E. (1968) A head-mounted three dimensional display. Fall Joint Computer Conference, 33, 757-764

Tirsoh E & Rabino S (1989) Physiotherapy for children with cerebral palsy. *American Journal of Diseases of Children* 143, 552-555.

Turnbull JD (1993) Early invention for children with or at risk of cerebral palsy. *Am. J. of Diseases of Children.*

Wann, J.P. & Rushton S.K. (1995a). The use of virtual environments in perception-action research: Grasping the impossible and controlling the improbable. in D. Glencross & J. Piek (Eds) *Motor Control and Sensory-Motor Integration.* Amsterdam: North-Holland.

Wann, J.P. & Rushton S.K.(1995b) Grasping the impossible: Stereoscopically presented virtual balls In B. Bardy, R. Bootsma & Y. Guiard. (Eds) *Proc. of the 8th International Conference on Event Perception and Action.* 207-210

Wann, J.P. & Rushton S.K. & Lee D.N. (1995) Can you control where you are heading when you are looking at where you want to go? In B. Bardy, R. Bootsma & Y. Guiard. (Eds) *Proc. of the 8th International Conference on Event Perception and Action.* 171-174

Wann J.P & Turnbull J. (1993) Motor Skill Learning In Cerebral Palsy: Movement, Action and Computer Enhanced Therapy. *Bailliere's Clinical Neurology 2, 15-28*

Warner D. & Jacobson L. (1992) Medical rehabilitation, cyberstyle. *AI Expert* 4, 65-72.

Wing A.M., Lough, S., Turton A., Fraser C. & Jenner J.R. (1990) Recovery of elbow function in voluntary positioning of the hand following hemiplegia due to stroke. *Journal of Neurology, Neurosurgery & Psychiatry* 53, 126-134.

Woodworth RS (1899) The accuracy of voluntary movement. *Psychological Review Monograph Supplements* 3, 3.