VIRTUALLY WALKING: FACTORS INFLUENCING WALKING AND PERCEPTION OF WALKING IN TREADMILL-MEDIATED VIRTUAL REALITY TO SUPPORT REHABILITATION

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Declaration

Whilst registered as a candidate for the above degree, I have not been registered for any other research award. The results and conclusions embodied in this thesis are the work of the named candidate and have not been submitted for any other academic award.

ABSTRACT

Psychomotor slowing, and in particular slow walking, is a common correlate of illness or injury, and often persists long after the precipitating condition has improved. Since slow walking has implications for long term physical and social wellbeing, it is important to find ways to address this issue. However, whilst it is well established that exercise programmes are good approaches to increase movement speed, adherence to therapy remains poor. The main reasons for this appear to be pain and lack of interest and enjoyment in the exercise.

Virtual Rehabilitation combines physical therapy with Virtual Reality (VR). This is a rapidly growing area of health care, which seems to offer a potential solution to these issues, by offering the benefits of increased patient engagement and decreased perception of pain. However, the question of how to encourage patients to increase their walking speed whilst interacting with VR has remained unanswered. Moreover, to maximise the benefits of this type of therapy, there needs to be a greater understanding of how different factors in treadmill-mediated VR can facilitate (or hinder) optimal walking.

Therefore this thesis investigated the factors influencing walking and perception of walking in treadmill-mediated VR, using a series of empirical investigations to determine the effect of a variety of factors in VR, which can then be applied in a clinical setting.

A review of the literature identified that high contrast stereoscopic virtual environments, calibrated to real-world dimensions, with a wide field of view and peripheral visual cues, are likely to facilitate accurate self-motion perception.

Empirical studies demonstrated that decreasing the visual gain (ratio of optic flow to walk speed) in VR can lead to a sustained increase in walk speed. However, these lower rates of visual gain are likely to be perceived as unrealistic, and may decrease immersion. Further investigation demonstrated that there is a range of visual gain which is perceived as acceptably normal, although even the lower bound of this acceptable gain is still higher than the optimum gain for facilitating faster movements.

Thus there is a trade-off between visual gain for realistic perception, and visual gain for improved walking speeds. Therefore other components that can improve walking speed need to be identified, particularly for those applications where reduction of the visual gain is undesirable.

Further empirical studies demonstrated that fast audio cues (125% of baseline cadence), in the form of a footstep sound, can increase the walk speed without disrupting the natural walk ratio. This effect was demonstrated in healthy populations, and also shown to be evident in a group of patients with chronic musculoskeletal pain. It was noted that in all the studies comparing a pain and non-pain group, the pain group walked more slowly across all conditions.

Additional empirical studies demonstrated that the use of self-paced treadmills for interfacing with VR was found to be associated with somewhat lower baseline walk speeds than normal overground walking, although the self-paced treadmills preserved the normal walk ratio. This slowing of walking and preservation of walk ratio was seen in both healthy participants and also in participants with chronic musculoskeletal pain. Therefore, whilst self-paced treadmills can support natural walking, additional factors need to be considered if treadmill-mediated VR is to be used to facilitate the increase in walking speeds desirable for rehabilitation.

Thus designing VR for rehabilitation is likely to involve consideration of a number of factors, and making individualised design decision based on specific therapeutic goals.

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Powell, W., Stevens, B., Hand, S., & Simmonds, M. (2011, March 19-23). Blurring the Boundaries: The Perception of Visual Gain in Treadmill-Mediated Virtual Environments. In *F. Steinicke & P. Willemsen (Eds)* Proceedings of the 3rd IEEE VR Workshop on Perceptual Illusions in Virtual Environments (pp4-8), Singapore: Suntec Conference Centre

Powell, W. A., Stevens, B., Hand, S., & Simmonds, M. J. (2010). Sounding Better: Fast Audio Cues Increase Walk Speed in Treadmill-Mediated Virtual Rehabilitation Environments. *Studies in Health Technology and Informatics*, 154, 202-207.

Powell, W. A., Stevens, B., Hand, S., & Simmonds, M. J. (2010), The Influence of Audio Cue Tempo on Walking in Treadmill-Mediated Virtual Rehabilitation (abstract), *Journal of CyberTherapy and Rehabilitation* 3 (2) 164-165

Powell, W., Stevens, B., & Simmonds, M. (2009). Treadmill Interface for Virtual Reality vs. Overground Walking: A Comparison of Gait in Individuals with and without Pain. *Studies in Health Technology and Informatics*, 144, 198-203.

Powell, W. (2008, April 5-10). Virtually Walking? Developing Exertion Interfaces for Locomotor Rehabilitation. *Paper presented at CHI, Florence, Italy.*

Powell, W., & Simmonds, M. (2008). Virtual reality: A healthy perspective (Editorial*). International Journal of Therapy and Rehabilitation,* 15(11), 480-481.

Powell, W. A., Stevens, B., Hand, S., & Simmonds, M. J. (2008). The influence of visual and auditory cues on pain and movement in a treadmill-mediated virtual environment. Poster presented at *Pain, Mind and Movement II - An Official Satellite Symposium of the XIIth World Congress on Pain*., Dublin, Ireland.

Powell, W., Stevens, B., Hand, S., & Simmonds, M. J. (2007). Software Gearing in a Virtual Environment: The Effect on Perception of Optic Flow. Annual Review of CyberTherapy and Telemedicine, 5, 99-106.

Powell, W., Hand, S., Stevens, B., & Simmonds, M. J. (2006). Optic Flow with a Stereoscopic Display: Sustained Influence on Speed of Locomotion. *Annual Review of CyberTherapy and Telemedicine, 4*, 65-70.

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1. INTRODUCTION

> *The overall aim of this thesis is to develop an improved VR toolset for the rehabilitation of patients with walking difficulties. It achieves this by a set of simple well-constructed experiments to determine the effect of a variety of factors in VR which can then be applied in a clinical setting.*

Generalised **psychomotor slowing** is a frequent correlate of pain and illness across a variety of health conditions (Harwood & Conroy, 2009), giving rise to a compromise in function (Ada, Dean, Hall, Bampton, & Crompton, 2003). In the early stages of illness or injury, slow movements can be beneficial to reduce the magnitude and direction of forces on the body. However, there is often a failure to recalibrate back to more normal movement patterns, leading to movements which are inefficient in terms of energy required (Simmonds, Goubert, Moseley, & Verbunt, 2006). This gives rise to reductions in activity and increasing disability (Hart, Martelli, & Zasler, 2000). Slow walking is a particular problem in this regard, as it decreases the ability to re-integrate into the community.

There are a variety of therapeutic approaches aimed at improving walking speed and quality, with overground and treadmill walking training being the most common. However, adherence to therapy is relatively poor (e.g. Forkan *et al*., 2006; Hardage *et al*., 2007; Hendry, Williams, Markland, Wilkinson, & Maddison, 2006; Resnick *et al*., 2007), and there remains a need for a more engaging and effective therapeutic approach.

Virtual Reality (VR) offers potential benefits for rehabilitation. It has been shown to increase engagement with therapy (e.g. Bryanton *et al*., 2006; Rizzo & Kim, 2005; Thornton *et al*., 2005) and provide distraction from pain (e.g. Hoffman, Richards, Coda, Bills, Blough, Richards & Sharar, 2004; Hoffman, Garcia-Palacios, Kapa, Beecher, & Sharar, 2003; Hoffman *et al*., 2001; Hoffman, Patterson & Carrougher, 2000).

If the analgesic properties of VR can be combined with an environment that improves movement speed, patients may be able to engage in rehabilitation at a higher functional level than traditional physical therapy, leading to increased long-term gains in mobility.

1.1 SLOW WALKING AND REHABILITATION

Slow walking is of particular concern in rehabilitation, being associated with a decrease in community ambulation (Ada, *et al*., 2003; Lord, McPherson, McNaughton, Rochester, & Weatherall, 2004), lower self-health ratings (Jylha, Guralnik, Balfour, & Fried, 2001), higher incidence of falls (Biderman, Cwikel, Fried, & Galinsky, 2002; Luukinen, Koski, Laippala, & Kivela, 1995) and an increased risk of cardio-vascular mortality (Dumurgier *et al*., 2009).

Patients are often discharged home with walking speeds less than 0.4m/s (Graham, Fisher, Berges, Kuo, & Ostir, 2010). However, full community-based ambulation requires **walk speed** of at least 0.8 m/s (Kuys, Bew, Lynch, Morrison, & Brauer, 2009), leaving a significant gap between acceptable function at discharge and the ability to reintegrate into community living.

In spite of the economic and health burden imposed by slowed walking, it continues to be a prevalent problem with, for example, only 7% of stroke survivors able to walk at a level commensurate with community participation (Ada, Dean, Lindley, & Lloyd, 2009). Indeed, much of the existing literature in the area of locomotor rehabilitation focuses on stroke rehabilitation, and this may in part be due to high prevalence (2.6%) of stroke in the population (e.g. Neyer *et al*., 2007). Since psychomotor slowing is an important consequence of stroke (Godefroy, Spagnolo, Roussel, & Boucart, 2010), it is unsurprising that there is a considerable focus on locomotor rehabilitation in this clinical group.

However, slow walking is a correlate of many other clinical conditions, and there is evidence that walking exercise rehabilitation programmes are effective for a wide range of patients. For example, it has been shown that regular walking can significantly reduce the pain associated with intermittent claudication (Gardner & Poehlman, 1995) and chronic musculo-skeletal pain (Ferrell, Josephson, Pollan, Loy & Ferrell, 1997), and also can reduce fatigue in cancer patients (Truong *et al*., 2011).

Whilst there is a wealth of research addressing various approaches to locomotor rehabilitation, there is also a wide range of opinion as to the most effective approach to improving walking speed, although Teasell *et al*. (2006) suggest that much of the research is of questionable quality. However, the most promising area of study seems to be focussing directly on **gait training**, with an emphasis on walk speed and **gait quality**.

A study that investigated the effects of speed-intensive overground walking, with and without **body weight support**, noted that the participants were capable of substantial increases in walking speed with sufficient verbal encouragement in a safe environment and that these speed increases were associated with an improvement in **step length** and improved **gait symmetry** (Lamontagne & Fung, 2004). Whilst these results are encouraging, there was no post-intervention testing reported, so it is not known whether the observed gait improvements could be sustained over time. In addition, participants were only tested on a 10m walkway and so it is not known if these increased speeds could be maintained for longer distances. This is a significant drawback in many overground **walking protocols**, as there is often a limited working area supported by the safety equipment, limiting the duration of walking which can achieved in a single test.

This limitation could be addressed by the use of a moving walkway or treadmill and it has been suggested that treadmill walking enforces more normal timing between the lower limbs, and facilitates the extension of the hips during stance phase, both of which are important biomechanical components of walking (Ada *et al*., 2003). However, concerns have been raised as to whether treadmill walking can be considered biomechanically equivalent to overground walking for the purposes of gait training. A recent study comparing overground gait kinematics with speed-matched treadmill walking concluded that the temporal gait parameters and leg kinematics in treadmill walking were sufficiently similar to overground walking to justify the therapeutic use of treadmills in place of overground training (Lee & Hidler, 2008). However, this study was carried out on a motorised treadmill at a preset speed, and it cannot be assumed that similar results would be found at different pre-set speeds, or on treadmills where walkers can dynamically adjust their walking speed.

1.1.1 TREADMILL GAIT TRAINING

A number of studies support the use of treadmills in locomotor rehabilitation for both long and short term improvements in gait (e.g. Ada *et al*., 2003; Pohl, Mehrholz, Ritschel, & Ruckriem, 2002; Sullivan, Knowlton, & Dobkin, 2002). However, there is little consistency in the approaches, making it difficult to establish the optimum protocols for such training programmes.

For example, a randomised trial that focussed on a combination of overground and treadmill walking, carried out on 29 post-stroke patients residing in the community, showed significant increases in walking speed and walking capacity (Ada, *et al*., 2003). The experimental group still showed a significant improvement compared with the control group at a 3 month follow-up. However, the study used a combination of treadmill training and overground walking in the intervention group, so it is not possible to identify the contribution of the treadmill training component to the improvements in gait. The researchers also noted that, although stroke patients generally increase walking speed by increasing **cadence** (step frequency), the experimental group demonstrated an increase in step-length. However, it should be noted that the rehabilitation programme was designed to focus specifically on techniques to improve step length (e.g. encouraging patients to step more slowly on a fixed speed treadmill), and so the improvement in step-length cannot be attributed to the walking practice alone but may be due to the conscious focus on increasing step length during rehabilitation.

A similar study of 24 stroke patients used treadmill training only, and compared the efficacy of 12 sessions of slow, variable and fast training on self-selected walking speed (Sullivan *et al.*, 2002). Treadmill training groups showed improvement in walk speed at 1 month and 3 month follow-up, with the greatest improvements associated with the fast training protocol. This study supports Lamontagne's finding that fast overground walking protocols improve walking quality (Lamontagne & Fung, 2004), and extends these results by demonstrating that treadmill training can be effective as a rehabilitation protocol, with improvements being sustained over time. Sullivan *et al.* (2002) noted that no significant improvements were found until after 6 training sessions, but the optimal number of training sessions was not established. In addition, the participants in this study were given varying levels of **body-weight support,** which was not analysed as a separate factor. The body-weight support was reduced as walking improved, but the contribution of body-weight support to the improvements in gait velocity is unclear.

A study that also used body-weight support, up to a maximum of 10%, also demonstrated clear benefits in **overground walking** following a speed-dependent treadmill training (STT) protocol (increasing the treadmill belt speeds gradually to the upper limits of the participants walking speed) (Pohl, *et al.*, 2002). This study compared STT, LTT (limited treadmill training - increasing the treadmill belt speeds by 20% across the training period) and conventional gait training (physiotherapeutic gait therapy based on the principles of the proprioceptive neuromuscular facilitation (PNF) and Bobath concepts). It was found that the STT protocol produced the largest improvements in gait, significantly improving both step length and cadence. Interestingly, limited treadmill training (LTT), which increased the treadmill belt speeds by 20% across the training period, still gave significant improvements compared with conventional gait training, demonstrating 85% improvements in overground walking speed. This does suggest that, although 'sprint' speeds appear to give the greatest benefit, even much more modest speed training still offers a great improvement in walk speed, with the participants in this study on the LTT protocol improving from 0.66 m/s (not commensurate with community ambulation) to 1.22 m/s (well above the speed required for community ambulation).

Whilst the benefits of treadmill training for recovery of gait post-stroke is now fairly well-documented, the mechanisms of this recovery are less well understood. However, a recent randomised controlled trial of 61 participants with chronic hemi-paretic stroke does suggest that neural plasticity in the cerebellum and mid-brain may be involved in the long-term brain adaptations associated with improvements in gait post-stroke (Luft *et al*., 2008). The study compared the effects on gait of a 6-month intervention of either treadmill exercise, or comparable duration stretching, and also carried out fMRI imaging studies to evaluate brain activation during limb movement. It was found that treadmill exercise improved walking velocity by 51% compared with stretching, and that this improvement in the treadmill group was associated with significantly increased activation in the cerebellum and midbrain during movement of the paretic limb. No similar change in brain activation was seen in the stretching group. These findings suggest that treadmill exercise is not just effective in improving muscle fitness and mobility, but may produce neuroplastic changes leading to long-term gains in functional outcomes.

A large number of the treadmill training studies have been carried out on stroke patients. However, there has been much less work investigating similar protocols across different clinical populations. Nevertheless, there is some evidence that treadmill training offers similar benefits in other clinical populations.

For example, a study comparing conventional physiotherapy (PT) with partial body weight support treadmill training (BWS-TT) in 80 patients with hip arthroplasty found that the BWS-TT group showed significantly greater improvements than the PT group, and these differences persisted at 3 and 12 month follow up. However, the main outcome measure of this study was the Harris Hip Score rather than walk speed, so although the intervention showed clear improvement in hip function, this cannot be assumed to generalise to improvements in capacity for community ambulation. However, it does suggest that the benefits of treadmill training are certainly not limited to stroke rehabilitation, and may offer improvements beyond walk speed increases.

Furthermore, a study to evaluate the effect of treadmill training in early Parkinson's Disease (PD) demonstrated similar results to those found with stroke patients (Pohl, Rockstroh, Ruckriem, Mrass, & Mehrholz, 2003). Single interventions of speed-dependent treadmill training (STT), limited treadmill training (LTT) and conventional gait training were assigned in random sequence to 17 patients with early Parkinson's Disease. Both of the treadmill interventions were associated with greater gains in walk speed than the conventional gait training. However, this study only used single interventions with no long-term follow-up, so it is not known whether the long-term gains noted with stroke patients (Pohl, *et al*., 2002) may also be possible with Parkinson's Disease.

In summary, the evidence suggests that treadmill training, and in particular at speeds above self-selected speed, offers significant immediate and long-term improvement in walk speed and gait quality in a variety of clinical groups.

1.1.2 LACK OF ADHERENCE TO THERAPY

Although the beneficial effects of exercise on general health and wellbeing as well as on physical function, and on psychological mood are now established, adherence to the recommended exercise and physical activity remains problematic, with many of the most effective interventions requiring a high level of input and encouragement from the therapist to ensure adherence to the treadmill protocols.

Whilst there has been research into effective approaches to physical therapy, there is also evidence that adherence to such therapy remains poor (e.g. Forkan, *et al*., 2006; Hardage, *et al*., 2007; Hendry, *et al*., 2006; Resnick, *et al*., 2007), particularly with respect to home-based exercise programmes where adherence is only around 42% (Hardage, *et al*., 2007).

Since the benefits gained in the early stages of physical therapy generally depend on continued activity or participation in exercise, it is important to identify the factors that contribute to this problem of lack of adherence to therapy.

A survey of 22 patients with osteoarthritis of the knee (Hendry, *et al*., 2006) highlighted a number of factors which impacted engagement with exercise, of which the most significant included pain and stiffness, lack of social support and boredom when exercising. Similarly, a survey of 179 elderly patients who had completed a therapist-supervised programme (Forkan *et al*., 2006) reported that the barrier most associated with reduced adherence was lack of interest or enjoyment in the exercise.

Therefore, an ongoing challenge in rehabilitation is how best to engage and motivate patients to actively participate in their own rehabilitation. However, some research has suggested that Virtual Reality may have the potential to facilitate engagement with therapy.

1.2 VIRTUAL REALITY AND REHABILITATION

Virtual Reality (VR) is a field of study that aims to create a system that provides a synthetic experience for its user(s) (Kim, 2005). There are various formal definitions of VR, but many are similar to that suggested by Craig, Sherman & Will (2009):

> *A medium composed of interactive computer simulations that sense the participant's position and actions, providing synthetic feedback to one or more senses, giving the feeling of being immersed or being present in the simulation.*

In recent years, VR has been emerging as a useful tool of both physical and psychological rehabilitation (Rizzo & Kim, 2005). As well as offering precise, repeatable control in a safe environment (Merians *et al.*, 2002; Rizzo & Kim, 2005; Sveistrup, 2004), it also provides a more engaging therapeutic experience (Bryanton, *et al.*, 2006; Rizzo & Kim, 2005; Thornton, *et al.*, 2005), which may be able to address some of the problems with adherence to conventional therapeutic programmes.

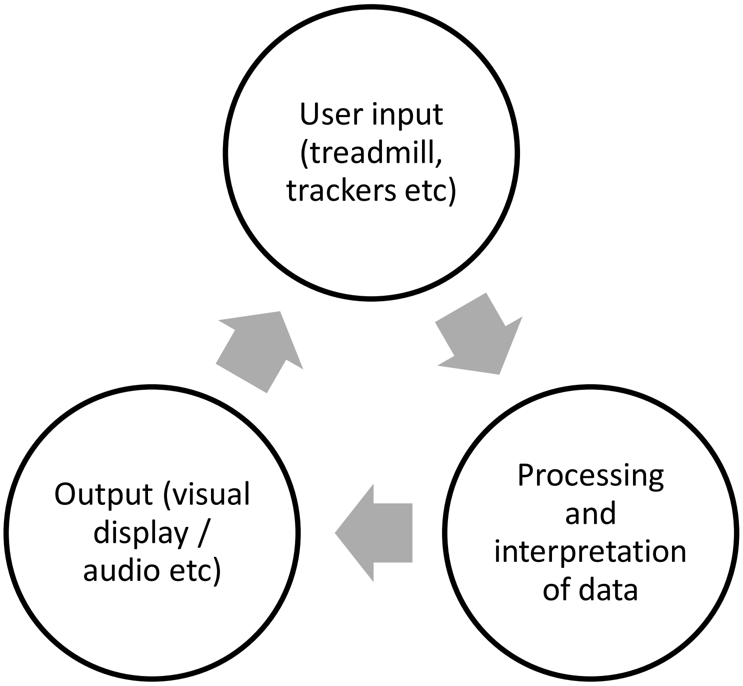

FIGURE 1.1: SIMPLIFIED DIAGRAM SHOWING THE COMPONENTS OF VIRTUAL REALITY FOR REHABILITAITON

In order to use VR for rehabilitation, it is necessary to have some input (to record the users movements), processing (process the input data and pass it to the VR software for analysis and action) and feedback, usually in the form of a display system which may include a **virtual environment** (e.g. computer generated 3D scene) and audio output. The user may respond to the output, thus altering the input (Figure 1.1).

Most of the early research into VR for rehabilitation relied on bespoke interfaces designed and built for an individual research group, such as the Rutgers Ankle System which is a 6-degrees-of-freedom device providing resistance to the foot whilst being used for VR exercise (Deutsch, Latonio, Burdea, & Boian, 2001). Rehabilitation studies have also taken place using haptic interface devices such as the Phantom® (a pen-like device which enables users to touch and manipulate virtual objects) (Bardorfer, Munih, Zupan, & Primozic, 2001) or Rutgers Master II-ND haptic glove (an instrumented glove with actuators to simulate object resistance) (Adamovich *et al*., 2005).

More recent work has developed to adapt full-body commercial interfaces such as the Sony EyeToy® (Rand, Kizony, & Weiss, 2004), the X-box Kinect™ (Chang, Chen, & Huang, 2011) and the GestureTek IREX™, which uses a video-capture interface and chroma-key screen to place the patient “in” the virtual environment (Bryanton, *et al*., 2006). Specialised software has been designed for applications ranging from rehabilitation of ankle movement in children with cerebral palsy (Bryanton, *et al*., 2006), through to balance retraining for brain-injured adults (Thornton, *et al*., 2005).

Attempts to identify the specific benefits of VR have identified 3 main areas that may offer particular benefits to locomotor rehabilitation. These are engagement or enjoyment of therapy (section 1.2.1), reduced perception of pain (section 1.2.2) and improved movement (section 1.2.3).

1.2.1 VIRTUAL REALITY AND PATIENT ENGAGEMENT

It is likely that patients will engage more with therapy if it is more enjoyable. Furthermore, Rizzo and Kim (2005) suggested that the interactivity of Virtual Reality may be able to distract patients by focusing on the visual engagement of the task. There are a number of successful studies that have used this technique to enhance enjoyment of physical therapy.

For example, Bryanton *et al*. (2006) evaluated the use of VR in children with Cerebral Palsy (CP). This study compared interactive VR with conventional exercise for ankle mobility. CP children are often non-compliant with the physical therapy required to reduce spasticity, and it was found that children with CP reported more fun and greater interest, performed more repetitions of the exercise, and generated more ankle dorsiflexion when using the VR game in comparison to standalone exercise. This supports the suggestion that greater enjoyment leads to more engagement with the therapy.

Similarly, a study of 27 adults with Traumatic Brain Injury (TBI) participated in 6 weeks of either activity-based or VR-based balance training, followed by focus group debriefing. Whilst both programmes demonstrated improvements in balance, the improvements were greater in the VR group and, in addition, this group expressed greater enjoyment than the activity-based group (Thornton *et al*., 2005).

The engagement benefits of interactive VR do not seem to be restricted to 3D interaction, and many researchers have been successfully employing the GestureTek IREX™ camera-based rehabilitation system, which uses a camera to extract the image of the patient from the surroundings and places it into a virtual environment, in which they interact in two dimensions with a variety of virtual objects. In spite of the restrictions in movement tracking associated with this type of system, researchers still report high levels of enjoyment as well as functional improvements. Kizony *et al*. (2003) reported on two case studies, one post-stroke and one spinal cord injury, both using the video capture system to play interactive games designed to improve reach and balance. Both participants reported enjoyment and a desire to repeat the experience, although the small size of the study precludes the ability to derive any statistical significance from the results.

Although only a small number of studies have directly measured engagement in virtual rehabilitation, the evidence to date suggests that VR may offer an enjoyable and engaging experience, which could increase adherence to therapeutic programmes, even in the absence of a supervising therapist (e.g. Bryanton *et al*., 2006).

1.2.2 VIRTUAL REALITY AND REDUCED PAIN PERCEPTION

Pain competes for finite attentional resources (Eccleston & Crombez, 1999; Grigsby, Rosenberg, & Busenbark, 1995; Hart, *et al*., 2000), and the use of distraction techniques can reduce the perception of pain (Hart, *et al*., 2000; Kleiber & Harper, 1999). The immersive properties of VR have been recognised for their ability to distract from attention to pain, and a number of research groups are now systematically studying this phenomenon (e.g. Gershon, Zimand, Lemos, Rothbaum, & Hodges, 2003; Hoffman *et al*., 2004; Hoffman, *et al*., 2003; Hoffman, *et al*., 2001; Hoffman, Patterson *et al*., 2000).

Furthermore, Hoffman *et al*. (2004) found a significant reduction in activity in the pain-related areas in the brain during interaction with VR, suggesting that the pain-reducing properties seen with VR are unlikely to be due to distraction alone.

There is compelling evidence that VR can contribute significantly to reduced pain perception, and this effect may be usefully exploited in VR-modulated locomotor rehabilitation.

1.2.3 VIRTUAL REALITY AND IMPROVED MOVEMENT

The goal of rehabilitation is to recover lost function, and with respect to motor rehabilitation this means improvements in endurance, speed and quality of movement, particularly with respect to **ADL** (activities of daily living). Therefore, if VR is to prove of benefit in rehabilitation, beyond the ability to increase engagement and reduce pain, then it must demonstrate the potential to facilitate improvements in motor function, and these improvements should be transferable to daily activities.

However, work is at an early stage and much of the research into VR and motor rehabilitation focuses on single cases or small pilot studies. This is in part due to the nature of VR in that it is still very much novel technology in this domain and, as such, it is not unreasonable to test the applications of the technology in this way.

For example, a single case-study of a 69-year old stroke patient using a bespoke interface for ankle rehabilitation found that over 6 training sessions there was improvement in force generation, endurance and co-ordination, and this improvement transferred to functional mobility, such as stair climbing and walking (Deutsch *et al*., 2001). A study of 3 stroke patients undergoing intensive exercise in VR for upper limb rehabilitation (Merians *et al*., 2002) had similar limitations, having no control or non-VR condition to compare to the VR condition. However, all the participants showed improvements in speed, mechanical work and finger fractionation, which were transferable to real-world activities. Likewise, another single case study of VR upper extremity rehabilitation for a stroke patient (Broeren, Rydmark, & Sunnerhagen, 2004), showed marked improvement in dexterity, grip force and endurance, which was transferable to ADL. However, none of these studies include control conditions, and so it cannot be concluded that the improvements were due to the VR component of the training. Also, similar results could be found using the same repetitive and intensive movements with a different mode of delivery. Furthermore, the studies are carried out on such small populations that they have no statistical significance. This is a common issue with much of the VR rehabilitation research. Many studies are small sample sizes with no control group and no valid outcome measures and therefore there is little scientifically meaningful information that can be derived

Nevertheless, these early studies contributed to the awareness and development of VR rehabilitation, demonstrating that therapy delivered via interactive VR could offer improvements in movement, whilst harnessing the advantages of very precise and controlled treatment and assessment, and increasing patient engagement. Sveistrup (2004) carried out one of the first reviews of VR motor rehabilitation, and although most of the studies discussed are small case studies, and often have no control condition, she does conclude that there was sufficient evidence to suggest that VR has a potential contribution to make in rehabilitation, and that the improvements achieved in VR may be transferable to ADL.

Considering a slightly larger study population (N=8), a study of stroke patients using VR for hand rehabilitation showed significant post-test improvements in hand function compared with the pre-intervention measures (Adamovich, *et al.*, 2005). However, once again there was no control group in this study, so the results may be solely due to the intensive therapy.

A similar size study using GestureTek's IREX system, which showed improvements in motor function associated with cortical changes, did include a control population (You *et al.*, 2005). However, the control group did not have a standard exercise intervention, but instead were a non-exercising control group, so although it showed a statistical improvement compared with no intervention, it still did not demonstrate any unique benefit of VR for rehabilitation.

A much larger study, of 50 stroke patients undergoing VR therapy for upper limb rehabilitation, again showed significant improvements in reaching movements and ADL assessment scores (Piron *et al.*, 2005). However, this study also did not use any control condition, and although they conclude that motor-recovery in post-stroke patients may be promoted by the enhanced feedback in VR, it is difficult to support this conclusion without comparative results from a non-VR rehabilitation condition.

However, a small study has been carried out on ten children with Cerebral Palsy that compared exercise performance in VR and non-VR conditions, which concluded that children generate a greater range of ankle dorsiflexion and report greater interest in the VR condition, compared with stand-alone exercise (Bryanton *et al.*, 2006). This study was one of the earliest to demonstrate that not only was VR for rehabilitation useful, but that it may offer additional benefits to conventional therapy, although the treatments were delivered in a counterbalanced manner so that all children received both treatment types, and thus there was no post-treatment comparison of their relative benefits.

In spite of the limitations of these studies, there are findings that emerge consistently and which do support the suggestions for further development of VR for rehabilitation. It is apparent that motor rehabilitation is not hindered by the use of VR, and that the movements learned in this way are transferable to real world tasks. However, more robust clinical studies, including randomised controlled trials and well designed single case studies, are necessary if there is to be sufficient evidence for widespread therapeutic application of VR.

It is notable that almost all the study examples reviewed are addressing upper limb rehabilitation, with little attention to locomotor rehabilitation. This may simply be due to the relative ease with which patients can interact with VR using the upper extremity. Most of the upper extremity systems use either video capture (e.g. Kizony, Raz, Katz, Weingarden, & Weiss, 2005; Sveistrup *et al*., 2003), sensor tracking (e.g. Viau, Feldman, McFadyen, & Levin, 2004) or glove-like interfaces(e.g. Adamovich, *et al*., 2005; Burdea, Deshpande, Langrana, Gomez, & Liu, 1997; Jack *et al*., 2001), and these are relatively low cost, simple to implement and commercially available. In contrast, lower limb rehabilitation poses additional challenges, as the most effective approach to locomotor rehabilitation, utilising treadmill training, currently requires proprietory interfaces for Virtual Reality, increasing both the complexity and the cost of the software and hardware.

Some studies of VR for lower limb rehabilitation utilise complex bespoke hardware, such as the Rutgers series of ankle interfaces (Boian, Burdea, Deutsch, & Winter, 2004; Burdea, Popescu, Hentz, & Colbert, 2000; Deutsch, *et al*., 2001; Girone, Burdea, Bouzit, Popescu, & Deutsch, 2001). More recently there have been developments in implementing treadmill interfaces to VR (Fung *et al*., 2004a; Fung, Richards, Malouin, McFadyen, & Lamontagne, 2006; Lichtenstein, Barabas, Woods Russell, & Peli, 2007), and whilst the approaches have been varied, the general principle remains the same, inasmuch as the walking movement of the patient on the treadmill is linked to the virtual movement through the Virtual Environment **(VE)**, as indicated by the **optic flow.** This gives the illusion of walking in the VE. Feasibility testing of these prototype interfaces suggests that they are able to be used by patients with locomotor dysfunction (e.g. Fung, *et al*., 2006).

Although improving movement is the explicit aim of VR for motor rehabilitation, there is no previous work specifically investigating the contribution of the factors in VR applications which may influence walking behaviour. Human walking is controlled by integrating visual, vestibular and proprioceptive information (Dietz, 2002), and this information would be expected to be congruent in a normal stable, real world, walking environment. However, it cannot be assumed that a virtual environment is perceived in the same way as a real environment, or that the sensory cues when treadmill walking will be integrated with it in the same way as they are in normal **overground walking**. Since walking behaviour is mediated by this sensory integration, it is possible that any perceptual or sensory differences between real and treadmill-mediated virtual environments may impact walking behaviour or self-movement perception.

1.3 THE RESEARCH QUESTION

Virtual reality offers potential for use in walking rehabilitation. However, given that there is a lack of previous research into the relationship between the factors within VR and human walking behaviour, it is difficult to make informed decisions when designing virtual reality for walking rehabilitation. This thesis therefore investigates the following question:

> *"How do factors within treadmill-mediated virtual reality influence walking and perception of walking?"*

1.4 CONTRIBUTION TO KNOWLEDGE

In addressing the research question (Section 1.3), this thesis makes the following contributions to knowledge:

1.4.1 IDENTIFICATION OF THE KEY FACTORS IN TREADMILL-MEDIATED VIRTUAL REALITY WHICH MAY INFLUENCE WALKING OR PERCEPTION OF WALKING

Most of the research to date in the field of virtual reality for rehabilitation has focussed on task performance and outcomes (Section 1.2), and has paid less attention to the components of the VR interface itself. However, it is important to identify factors within VR which may facilitate or inhibit the desired movement outcomes (chapter 2), in order to identify and optimise their role in virtual reality for rehabilitation.

Chapter 2 identified the factors in VR which are most commonly found in treadmill-mediated applications, and identified five main areas which may significantly affect movement or movement perception and therefore which warrant further investigation. The factors identified are: rate of optic flow (section 1.4.2); distortion of optic flow perception in VR (section 1.4.3); audio tempo (section 1.4.4) and issues with the use of a treadmill interface (section 1.4.5). In addition, healthy populations may respond differently than clinical populations (sections 1.4.6 and 1.4.7).

Whilst most of these factors have been discussed independently in previous research, this is the first review evaluating multiple components of VR with respect to their potential impact on walking and perception of walking in VR for rehabilitation.

1.4.2 INVESTIGATION OF THE SUSTAINED MODULATING EFFECT OF OPTIC FLOW ON TREADMILL WALKING

During normal walking, multiple congruent sources of sensory information provide feedback to control walking speed (Section 3.1). However, creating a conflict in the visual component of this control system (optic flow) can lead to a recalibration of motion (Section 3.2). Although previous work identified that altering the optic flow in a virtual environment can influence walking speed for short durations, it was not clear whether the effects would wash out or persist over time, or whether they could potentially be sustained for the duration of a therapeutic intervention (Section 3.2).

Therefore an empirical study was undertaken to investigate whether the effects of optic flow are sustained over time (Section 3.3). This is the first study to demonstrate the modulating effect of optic flow on walking over several minutes.

1.4.3 INVESTIGATION OF THE TOLERANCE OF CHANGES IN VISUAL GAIN IN TREADMILL-MEDIATED VIRTUAL REALITY

Visual gain is the ratio between the presented rate of optic flow and the current speed of self motion. In normal overground walking the visual gain would be 1:1. However, there is a perceptual distortion of the speed of optic flow in VR. Previous research has indicated that optic flow in VR needs to be faster than the walk-speed of the user (section 4.1) for it to appear normal (visual gain>1:1) which may have implications for the ecological validity of treadmill-mediated virtual reality. However, it is not clear from previous work whether there is a tolerance for changes in visual gain.

Therefore an empirical study was undertaken to investigate whether there is a range of visual gain which is tolerated as normal, and to attempt to quantify the upper and lower boundaries of gain tolerance (Section 4.2.1). Previous studies have been based on variations of the staircase method of psychophysical evaluation, which is designed to identify a perceptual boundary. To identify and quantify a range of perceptual tolerance requires a different methodological approach. The study was the first to identify a range of visual gain values which lie within the tolerance of normal gain perception. Furthermore, this is the first study to use the ‘perceptual range’ approach to the investigation of visual gain perception, and to identify it as a useful methodology for investigating perceptual distortions in VR. This approach may be useful for similar studies investigating, for example, depth compression in VR.

Visual gain changes can either be made overtly (with participants being alerted to the change) or covertly (gradual changes without informing the participant), but there is no research comparing these two approaches to identify if they produce different results. This can make it difficult to design a study which will elicit the most accurate and relevant results. Therefore this study compared covert and overt visual gain change conditions, in order to identify any difference in the perception of gain between the two methods (section 4.2.1). This study was the first to demonstrate that the perceptual tolerance of visual gain is dependent on the changes to visual gain being made covertly.

1.4.4 THE EFFECT OF AUDIO CUE TEMPO ON WALKING IN TREADMILL-MEDIATED VR

There is a strong link between auditory rhythms and motor activity, and studies in non-VR settings indicate that the use of **audio cueing** can facilitate improved walk speed and quality (section 5.1.1). However, although there is evidence that fast **audio cue tempo** may be associated with faster walking speeds, it is not known whether interaction with VR may also interact with any potential effect of audio cues on walking speed. Furthermore, there is a lack of data relating to self-paced treadmill walking with audio cueing (section 5.1.1).

Therefore, an empirical study was conducted to investigate the influence of audio cue tempo on self-paced treadmill walking in VR (section 5.2).

The contribution to knowledge from this experiment was to demonstrate the modulating effect of audio cue tempo on treadmill walking in VR, with fast audio cues being associated with faster walk speeds. This knowledge could help to inform the design of the audio components of VR rehabilitation applications, in order to optimise the facilitation of walking outcomes.

1.4.5 A COMPARISON OF OVERGROUND AND TREADMILL WALKING SPEEDS

It has been observed that treadmill walking tends to be associated with a lower walk speed than overground walking (sections 3.5 and 5.4). This could have implications for the use of treadmill-mediated VR for walking rehabilitation, but there is no data comparing self-selected walk speeds overground and on a treadmill, either in healthy populations or in patients with pain.

Therefore an empirical study was conducted to compare the overground and treadmill walking speeds and cadence in participants with and without pain (section 7.2). The contribution to knowledge from this experiment was to demonstrate the slower walking speeds when walking on a self-paced treadmill compared with overground walking. These findings can help to inform decision making in both the design of VR applications for walking rehabilitation, and also in the selection of appropriate walking protocols to take into account the altered walk speed.

1.4.6 THE EFFECT OF AUDIO CUE TEMPO AND OPTIC FLOW RATE ON PATIENTS WITH PAIN

Chapter 3 demonstrated that changing optic flow can increase walk speed, and chapter 5 demonstrated that fast audio cue tempo can also increase walk speed. However, both these studies were carried out on normal healthy adults and it is not known whether the effects would be similar in a clinical population with chronic pain.

Therefore an empirical study was conducted to investigate the influence of audio and visual cues on walking in a population with musculoskeletal pain (section 7.2).

The contribution to knowledge from this experiment was to demonstrate the potential for the use of audio to increase walk speed in treadmill-mediated VR for patients with musculoskeletal pain. This extends the previous findings (Chapter 5) by demonstrating that the effect of audio cues can be applied to a clinical population.

1.4.7 THE EFFECT OF AUDIO AND VISUAL CUES ON PERCEIVED PAIN

It appears that individuals with pain can move faster but don't, perhaps due to the anticipation of pain with faster movement and thus a therapeutic approach which can facilitate faster movements without the deleterious effects of the anticipation of pain may be able to offer improvements in walk speed for patients with musculoskeletal pain (section 7). However, it is not known whether increased walk speeds in treadmill-mediated VR will be associated with higher levels of perceived pain.

Thus a further contribution to knowledge from the experiment in chapter 7 is to demonstrate the influence of audio cues and optic flow on reducing perceived pain during treadmill walking.

Based on the main findings of the empirical studies, this thesis adds to the understanding of how individual factors in VR influence movement and perception of movement in treadmill-mediated virtual reality, and highlights areas where further work is necessary to support fully informed design of VR for walking rehabilitation.

1.5 THESIS ORGANISATION

Chapter 2 presents a critical review of the VR factors that potentially influence walking and perception of walking in treadmill-mediated VR. These components are investigated further by empirical study in chapters 3 - 7.

Chapter 3 details a study investigating the effect of sustained modulations of optic flow on walking speed (Powell, Hand, Stevens, & Simmonds, 2006). It also identifies a potential conflict between optic flow for improving walking, and optic flow for realistic speed perception.

Chapter 4 addresses the issue identified in chapter 3, and details a study investigating the tolerance to changes in visual gain in treadmill-mediated VR, and identifies the boundaries of the gain tolerance, and the influence of visual clutter on the perception of gain (Powell, Stevens, Hand, & Simmonds, 2011). It concludes that it is necessary to identify further factors in VR to improve walking where slow optic flow is not appropriate.

Chapter 5 attempts to identify a further factor which can address the issue identified in chapter 4, and details a study investigating the effect of audio cue tempo on walking in treadmill-mediated VR (Powell, Stevens, Hand, & Simmonds, 2010). This chapter also highlights the fact that treadmill walking appears to be slower than overground walking, and suggests that this needs further investigation.

Chapter 6 addresses the issue raised in chapter 5 and details a study comparing walking on a self-paced treadmill with overground walking (Powell, Stevens, & Simmonds, 2009).

The results of chapters 3 and 5 indicate that it may be possible to increase walking speed in treadmill-mediated VR by manipulating optic flow and audio cues. Since the motivation for these studies was to identify factors in VR which could facilitate walking rehabilitation, it was felt to be important to conduct an experiment to ascertain whether the effects would be similar in a clinical population. As pain can cause significant slowing of walking, even without any other physical or neurological impairment, it was felt that a group with pain on walking would be a suitable initial clinical study group.

Chapter 7 details a study investigating the effect of visual flow and audio cues on walk speed in people with and without pain (Powell, Stevens, Hand, & Simmonds, 2008).

Chapter 8 presents the conclusions of the research programme, and discusses the main contributions to knowledge together with the implications for the design of treadmill-mediated VR for rehabilitation, and suggestions for further research.

2. CRITICAL REVIEW OF THE FACTORS IN VR WHICH MAY INFLUENCE MOVEMENT OR PERCEPTION OF MOVEMENT DURING WALKING REHABILITATION

2.1 INTRODUCTION

Virtual Reality may offer the potential for enhanced movement in rehabilitation, and current research indicates that it supports the performance of the type of repetitive therapeutic tasks commonly used in physical therapy. Most of the research in this field to date has focussed on task performance and outcomes, and has paid less attention to the components of the VR interface itself. However, since VR is being advocated as a useful tool for movement rehabilitation (Holden, 2005; Rizzo & Kim, 2005; Sveistrup, 2004), it is important to identify factors within VR which may facilitate or inhibit the desired movement outcomes. In order to identify those factors which are most likely to influence movement, it is necessary to conduct a critical review of the VR components which may affect movement.

2.2 COMPONENTS OF VIRTUAL REALITY FOR WALKING REHABILITATION

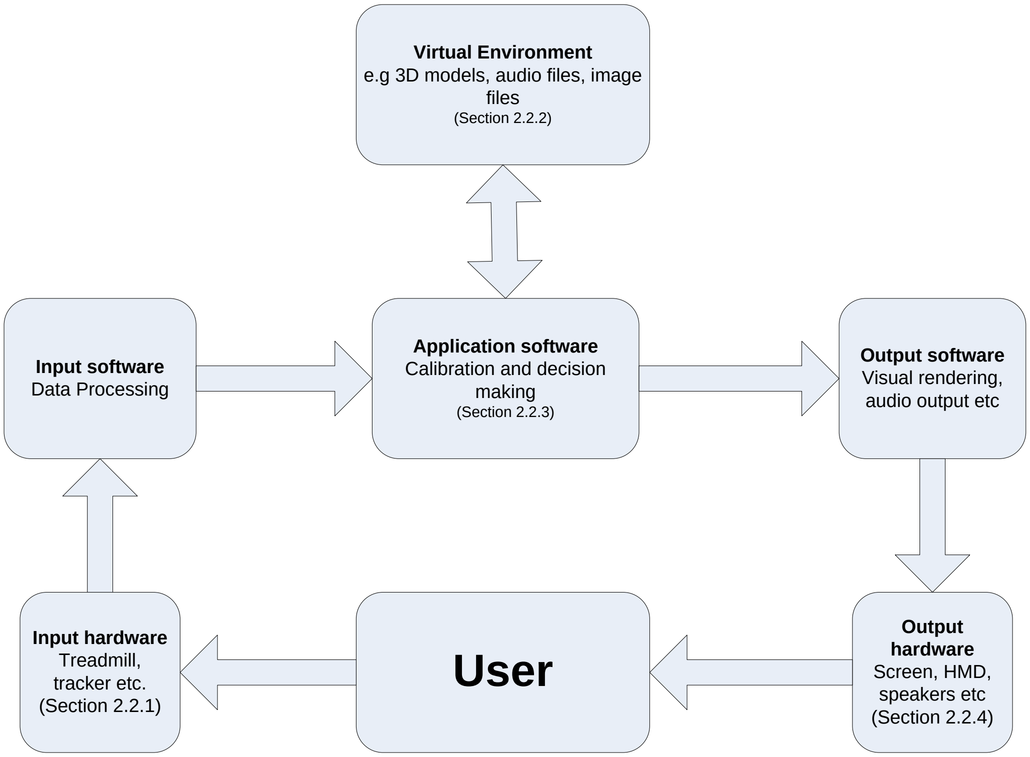

FIGURE 2.1: TYPICAL COMPONENTS OF VR SYSTEM FOR REHABILIITATION

Virtual reality is generally accepted to consist of input (section 2.2.1), a virtual environment (section 2.2.2), and output to one or more of the senses (section 2.2.4). Whilst the details may vary widely for different applications, most VR systems for walking rehabilitation will include these components in some form. The VR software communicates between these components (Figure 2.1) and also calibrates the output (e.g. size of rendered environment, rate of change of visual and audio content etc) (section 2.2.3).

2.2.1 INPUT

There are three main types of device that can convert the movement of a user into meaningful input into the VR rehabilitation application software.

a. Bespoke mechanical devices (section 2.2.2.1) which are directly controlled by the lower limbs of the user, such as the Rutgers Ankle system (Boian, *et al.*, 2004; Deutsch, *et al.*, 2001).
b. Optical or magnetic tracking systems (section 2.2.1.2), which are generally used during overground walking, record the real-time position of a set of markers worn by the user, and continuously update this data into the VR application (Durgin, Fox, Schaffer, & Whitaker, 2005; Slater, Usoh, & Steed, 1995; Templeman, Denbrook, & Sibert, 1999; Usoh *et al.*, 1999).
c. Treadmills (section 2.2.1.3) that can be interfaced to a VR application, for example by using an optical sensor to read belt movement (Apfelbaum, Pelah, & Peli, 2007; Durgin, Gigone, & Scott, 2005; Fung, *et al.*, 2004a; Fung, *et al.*, 2006; Kassler, Feasel, Lewek, Brooks, & Whitton, 2010; Lichtenstein, *et al.*, 2007; Mohler *et al.*, 2007; Thurrell & Pelah, 2005)

2.2.1.1 BESPOKE MECHANICAL INPUT DEVICES

The mechanical devices, by design, enforce specific and precise movements of the lower limb in order to interact with the virtual environment. Whilst clearly this type of input device directly influences the movement performed by the user, this is not a by-product of its use, but its main purpose, and therefore is not considered further in this thesis.

2.2.1.2 MOVEMENT TRACKING SYSTEMS

Tracking systems can be used to either allow free walking in an open space (e.g. Durgin, *et al.*, 2005; Peck, Fuchs, & Whitton, 2011; Suma *et al.*, 2011), or to interpret stepping-in-place movements to simulate walking (Slater, *et al.*, 1995; Templeman, *et al.*, 1999; Usoh, *et al.*, 1999; Zielinski, McMahan, & Brady, 2011).

Slater (1995) reported that there was little difference in user preference between mouse navigation and stepping in place. He attributes this to deficiencies in the neural network used to interpret the stepping motions. However, even with a more robust neural network, it is not certain that stepping in place (a motor activity more associated with climbing) would be acceptable as a natural mapping to virtual walking on a flat surface. Indeed, a follow-up study by Usoh *et al*. (1999) indicates that the strongest sense of user presence in the virtual environment was associated with natural walking, and this walking method was also perceived as the most simple, straightforward and natural.

Walking freely whilst viewing a head-mounted display offers the advantages of user-controlled pace and more natural motion, but few researchers or rehabilitation therapists have access to the large open spaces required for this approach, and position tracking over wide spaces is complex and expensive (Lichtenstein, *et al*., 2007). An alternative approach to full free-walking is to use **redirected walking** (Neth *et al*., 2011; Peck, *et al*., 2011), but this requires pauses and turns in navigation, and still requires a large walking space.

Tracking systems have been used with varying degrees of success to simulate walking in VR, but the studies to date have mainly focused on comparing different ways of simulating walking in VR and the effect on presence (Slater, *et al*., 1995; Templeman, *et al*., 1999; Usoh, *et al*., 1999). However, there is little evidence regarding the impact the use of the tracking itself may have in altering the walking behaviour, or any effect on the users' perception of their own movement. Nevertheless, the particular constraints on walking imposed by the use of tracking and free overground movement make this approach less practical for extended walking rehabilitation, and therefore will not be considered further in this thesis.

2.2.1.3 TREADMILL INPUT DEVICES

Treadmill interfaces to VR are becoming increasingly widely used (Apfelbaum, *et al*., 2007; Durgin, Gigone, *et al*., 2005; Fung *et al*., 2004b; Fung, *et al*., 2006; Kassler, *et al*., 2010; Lichtenstein, *et al*., 2007; Mohler, *et al*., 2007; Thurrell & Pelah, 2005), which may in part be due to the fact that they appear to offer relatively natural movement, similar to overground walking, whilst still allowing accurate correlation between the walking behaviour of the user and the movement in the virtual environment (c.f bespoke mechanical devices in section 2.2.1.1). In addition, they require less space than free-walking using trackers (Lichtenstein, *et al*., 2007). There is considerable evidence of the benefits of treadmill use in non-VR gait training (section 1.1.1) and thus it seems a logical input device to use for VR for rehabilitation.

There are three main categories of treadmill, each requiring a different approach to locomotion. The simplest are non-motorized treadmills ("self-driven") which require the belt to be driven by the walking effort of the subject (Apfelbaum, *et al.*, 2007; Lichtenstein, *et al.*, 2007). These typically have fairly narrow and short walking surfaces and often are slightly inclined to facilitate belt movement. More commonly used are motor-driven treadmills ("fixed-speed"), which can have a much wider and longer walking surface (Durgin, Reed, & Tigue, 2007; Durgin, Gigone, *et al.*, 2005; Mohler, *et al.*, 2007). Most of these motorized treadmills run at speeds, which, although they can be altered incrementally by the user or operator, typically allow no dynamic real-time natural variation in speed. The third category of treadmill (“self-paced”) allows much more natural movement and therefore could be well suited to traversal through virtual environments. The speed of these "self-paced" treadmills is dependent on the instantaneous walk speed of the user. The motor speed is updated in real-time to keep the user in the centre of the treadmill belt whilst accommodating natural fluctuations in walk speed (Fung, *et al.*, 2006).

Whilst some studies have suggested that there is little difference in walking overground or on a treadmill (Alton, Baldey, Caplan, & Morrissey, 1998; Lee & Hidler, 2008), there is also evidence which indicates that there are significant differences in some walking parameters when treadmill walking is compared with overground walking (Alton, *et al.*, 1998; Durgin, *et al.*, 2007; Stolze *et al.*, 1997; Varraine, Bonnard, & Pailhous, 2002). Further investigation is needed to understand the ways in which normal walking may be influenced by the use of a treadmill as an input device for VR (chapter 6).

2.2.2 VIRTUAL ENVIRONMENT

A virtual environment can be considered as a three dimensional data set describing an environment based on real-world or abstract objects and data (Stanney, 2002). In reality this tells us little about the main components of a typical environment used for virtual rehabilitation. Typically VR rehabilitation systems will deliver visual and audio content, and thus the virtual environment is likely to be made up of 3D models, image files and audio files, which are then processed by the application software.

2.2.2.1 VISUAL CONTENT

The majority of studies using walking interfaces to VR use visual stimuli to simulate movement, and these visual components fall into two broad categories – abstract or realistic. The abstract visuals are typically patterns of dots or lines, designed to induce **vection** when they are moving (Frenz, Lappe, Kolesnik, & Buhrmann, 2007; Pailhous, Ferrandez, Fluckiger, & Baumberger, 1990; Thurrell & Pelah, 2005). Realistic visuals are more commonly used in environments designed for rehabilitation, and they are typically hallways (Durgin, *et al*., 2007; Durgin, *et al*., 2005; Fung, *et al*., 2006; Lichtenstein, *et al*., 2007; Mohler *et al*., 2004; Mohler, *et al*., 2007; Varraine, *et al*., 2002) or street scenes (Boian, *et al*., 2004; Fung, *et al*., 2004; Fung, *et al*., 2006).

Very few of the studies offer any rationale for the choice of environment, except where a street crossing is being used for task-specific training (e.g. Boian, *et al*., 2004). Hallways and street scenes are relatively easily constructed from repeating 3D modules, as well as providing clear peripheral cues, and this may be why they are most commonly used for this type of study. However, without rationale or comparative investigations, it is not known whether the scene itself may influence walking. Indeed, more open environments such as park scenes have also been used (Fung, *et al*., 2006), but these have not been directly compared to the closed environments. Additionally, previous research has indicated that visual clutter may influence perception of movement speed (Durgin, *et al*., 2005), although it is not clear whether the difference was due to the increase in number of visual cues, or the presence of virtual obstacles. If VR is to be used for walking rehabilitation, it is important to know whether visual clutter (without virtual obstacles) does improve the accuracy of speed perception, and this warrants further investigation (chapter 4).

In addition, there is some evidence that the presence or absence of peripheral visual cues may alter the accuracy of self-movement perception (Banton, Stefanucci, Durgin, Fass, & Proffitt, 2005), and it has also been postulated that the influence of optic flow may be greater when the optic flow stimulus is similar in pattern to that encountered during everyday locomotion (Thurrell & Pelah, 2002). This suggests that the hallway or street scenes may offer more realistic self-motion perception than open parkland scenes.

Furthermore, there is evidence that the perception of movement speed may be in part dependent on the level of contrast in the moving scene, with higher contrast visual cues appearing to move more quickly than those with lower contrast (Stone & Thompson, 1992).

2.2.2.2 AUDIO CONTENT

Whilst a number of studies mention the use of noise-cancelling headphones to eliminate external sounds (Banton, *et al*., 2005; Prokop, Schubert, & Berger, 1997; Thurrell & Pelah, 2005), there is a remarkable lack of discussion of the use of audio within the virtual environments. In the majority of video games, and commercial virtual reality applications, sound effects and music are an intrinsic part of the virtual environments, and indeed it may be considered to be as important as the visual content (Magnenat-Thalman, Kim, Egges, & Garchery, 2005). However, it should not be assumed that music or sound effects can be included in the environments simply to enhance **immersion** and enjoyment, without consideration of the potential direct influence such audio components may have on movement.

It is known that music can alter gait during exercise (Cluss, Crane, Gross, & Frederickson, 2006), with different types of music having different effects on gait (Ahmaniemi, 2007; Karageorghis *et al*., 2009; Karageorghis & Terry, 1997). At a more fundamental level, the underlying tempo of the music may also have a profound effect on movement, with an increased beat frequency being associated with faster walk speeds (Lim *et al*., 2005; Styns, van Noorden, Moelants, & Leman, 2007; Suteerawattananon, Morris, Etnyre, Jankovic, & Protas, 2004) and improved gait quality (del Olmo, Arias, Furio, Pozo, & Cudeiro, 2006; Roerdink, Lamoth, Kwakkel, van Wieringen, & Beek, 2007). However, to date, there is little research into the effect of audio on movement when interacting with virtual reality.

Since the non-VR studies indicate significant effects of audio on walking, it is important to establish whether audio has a similar influence on walking in VR (chapters 5 and 7).

2.2.3 CALIBRATION

Visual realism in a virtual environment is mainly measured by dimensions of geometry such as length, volume and area (Magnenat-Thalman, *et al*., 2005), and therefore careful calibration of the virtual environment is necessary so that its elements appear realistic in size and proportions. It is not known whether incongruous dimensions of virtual elements affect movement directly, but since visual input contributes significantly to self-speed estimation (Durgin, *et al*., 2005; Konczak, 1994; Mohler, *et al*., 2004; Pailhous, *et al*., 1990; Prokop, *et al*., 1997; Warren, Kay, Zosh, Duchon, & Sahuc, 2001) it is reasonable to assume that misleading dimensions in the virtual environment are likely to influence perceived movement speeds.

If a treadmill is to be used to interface to a virtual environment, then dynamic calibration also needs to be considered, i.e. the conversion of the physical movement of the treadmill belt to translation in the virtual environment. If the environment is built to reflect real-world dimensions, then it would seem logical to calibrate the interface such that for every metre walked on the treadmill, the user advances one meter in the virtual environment. However, there is evidence that there is an altered perception of the speed of optic flow when treadmill walking in a virtual environment (e.g. Distler, Pelah, Bell, & Thurrell, 1998; Durgin *et al*., 2005). For optimal design of treadmill-mediated interaction, if the perceived realism of the rate of progression through the environment is important, it is necessary to fully understand both the magnitude and direction of this altered perception.

Although there are some studies which attempt to quantify this misperception of optic flow (Banton, *et al*., 2005; Distler, *et al*., 1998; Durgin, *et al*., 2007; Durgin, Fox *et al*., 2005; Durgin, Gigone, *et al*., 2005; Kassler, *et al*., 2010), they differ significantly in their findings, and are difficult to compare directly due to considerable differences in methodology. Furthermore, they do not offer any insight into what range of optic flow rates may be tolerated as realistic. For optimal design of virtual environments for walking rehabilitation, it is important to understand how different rates of optic flow are perceived (chapter 4).

In addition to the significance of misperception of optic flow in VR, there is also evidence that the rate of optic flow can directly influence the speed of walking, with slower optic flow speeds being associated with faster walking speeds (Konczak, 1994; Prokop, *et al*., 1997; Schubert, Prokop, Brocke, & Berger, 2005).

If walking speed can be manipulated by varying optic flow, then this could be of benefit for walking rehabilitation in VR. However, studies of this phenomenon to date have concentrated on modulations over short time scales, typically of a few seconds duration (e.g. Konczak, 1994; Pailhous, *et al*., 1990). To date there are no studies investigating the sustained effect of optic flow on walking. However, if there is to be a practical application for rehabilitation or training then the effect needs to be sustained for longer time periods. Further investigation is thus necessary to establish this (chapter 3).

2.2.4 OUTPUT

For the purposes of VR for walking, the main channels for feedback to the users' senses will be visual and auditory (section 2.2.2).

Visual feedback can be delivered either via a projection screen, a computer monitor or through a head-mounted display (HMD). Factors such as display size, field of view, display resolution, refresh rate and colour fidelity vary between different output devices. In addition, the display can be monoscopic or stereoscopic.

There is a lack of research into the direct effect of resolution, refresh rate or colour fidelity on walking or perception of walking. Whilst it is possible that these factors may be significant, it is beyond the scope of this thesis to address them all, and therefore they will not be investigated further.

However, there are four main factors which will need to be taken into consideration with respect to the design of the visual output for any study:

a. Display type (HMD, projection screen or computer monitor)(section 2.2.4.1)
b. Screen size (section 2.2.4.2)
c. Field of view (section 2.2.4.2)
d. Stereoscopic vs. monoscopic display (section 2.2.4.3)

In addition to visual considerations, audio content may be delivered to the user via headphones or speaker systems, and can vary in volume and fidelity. Manipulation of audio fidelity is outside the scope of this thesis, and volume can be varied during delivery of the application regardless of the audio delivery hardware. However, only one factor will have to be considered for any study with respect to audio output hardware:

e. Headphones vs speaker systems (section 2.2.4.4)

2.2.4.1 DISPLAY TYPE

Head mounted displays offer the advantage of enclosing the user in the virtual environment, preventing visual intrusion of the real physical world during immersion in the virtual environment. They also allow the user to turn in any direction without losing sight of the visual output. However, they often have a reduced field of view compared with large screen displays, and may also be uncomfortable to wear for long periods. In addition, heightened vigilance is necessary from researchers or therapists to ensure safe movement, as the user will be unaware of their precise location in the physical world and thus unable to navigate themselves around obstacles. This could be of particular concern when using a treadmill interface, as the user could inadvertently step off the treadmill.

The main difference between monitor-based displays and projection screens is the size of the display, with projection screens generally being significantly larger than computer monitors (section 2.2.4.2).

There are fewer safety and comfort concerns with screens compared with HMDs, but they also allow the physical world to visually intrude on the virtual environment, and thus a user would be able to see the treadmill when using a large screen display.

For applications where free movement is desirable, or it is important to occlude the view of the physical world, HMDs offer an advantage. However, where the user is already constrained to face in one direction, as with a treadmill interface, a large screen display may be the preferred option. Indeed, the majority of studies using treadmill interfaces to VR have been carried out using large screen displays (e.g. Apfelbaum, *et al*., 2007; Fung, *et al*., 2006; Lichtenstein, *et al*., 2007; Mohler, *et al*., 2007; Thurrell & Pelah, 2005; Varraine, *et al*., 2002), with the notable exception being Durgin *et al*. (2005), who were making a direct comparison between overground walking and treadmill walking in VR, which precluded the use of a screen. However, again the studies involved are generally small and do not directly address the issues associated with different display types.

Furthermore, a comparison of the effect of both HMD and **back-projection** screens on the perception of self-motion in VR found that the HMD was associated with higher levels of perceptual distortion (Riecke, Schulte-Pelkum, & Bulthoff, 2005).

2.2.4.2 SCREEN SIZE AND FIELD OF VIEW

Except when an HMD is used, the field of view in the virtual environment will be determined to a certain extent by the size of the screen and the position of the user, and therefore screen size and field of view are considered together.

Although a screen display cannot offer the full visual immersion of a HMD, a large screen can offer a reasonable alternative, and may indeed provide a wider field of view than most HMDs. Previous studies have indicated that the presence or absence of peripheral visual cues may alter the accuracy of self-movement perception (Banton, *et al*., 2005), with a wider field of view allowing more accurate perception. The normal field of view is around 200^{o} horizontal and 135^{o} vertical (Creem-Regehr, Willemsen, Gooch, & Thompson, 2005). However, an HMD with a total vertical FOV of 35^{o} and total horizontal FOV of 42^{o} did not significantly affect distance perception (Creem-Regehr, *et al*., 2005). Therefore displays which offer a field of view similar to this may be suitable for use in VR for walking rehabilitation. Conversely, displays offering a wider field of view may be unnecessary. Thus the ideal display setup would be a user (treadmill) position and screen size which allows a field of view between 42^{o} and 200^{o}.

2.2.4.3 STEREOSCOPIC VERSUS MONOSCOPIC DISPLAY

Many of the VR-walking studies do not identify whether they used stereoscopic or monoscopic displays, and those that do supply these details (e.g. Fung, *et al*., 2004; Mohler, *et al*., 2004; Thurrell & Pelah, 2005) do not comment on any potential differences between the two display methods. However, there is some evidence that induction of self-motion perception is stronger in stereoscopic VR than in monoscopic VR (Palmisano, 1996), and thus this should be taken into consideration when perception of self-motion is important. In addition, depth judgements in VR have been found to be more accurate using binocular disparity rather than shading or other monocular depth cues (Durgin, Proffitt, Olson, & Reinke, 1995).

There are a number of techniques in common use for delivering stereoscopic content, for example active stereo using shutter glasses, passive stereo using polarised light, autostereo using lenticular screens, and anaglyphic stereo (red/green or red/cyan filters). However, with the exception of anaglyphic stereo (which causes colour distortion), all the methods deliver a similar stereo experience for straight-ahead viewing, and so the precise delivery mode of the stereoscopic content will not be considered further in this thesis.

2.2.4.4 HEADPHONES VERSUS SPEAKER SYSTEMS

There is little discussion in the literature of the use of audio within the virtual environments (section 2.2.2.2), and although there are non-VR studies, which suggest that audio may have significant effects on walking, there is a lack of data comparing headphones and speaker systems in VR.

More recent developments have enabled the production of binaural sound, and this can be delivered by headphones but not by speakers (due to cross feed). However, it is not currently in widespread use as it is complex to produce, and is unlikely to significantly influence VR system design decisions at the present time. Since both speakers and headphones can deliver mono and stereo audio, it would seem that there is little difference between the two delivery modes with respect to any potential influence on movement or perception, although headphones may offer a slight advantage by reducing extraneous noise, which may be important if sound can influence movement.

2.3 REVIEW OF KEY FACTORS

The design of virtual reality for walking rehabilitation is complex, and involves multiple factors which may interact with each other and with the user in unpredictable ways. However, this chapter has identified some key components which are likely to influence walking or perception of walking in treadmill-mediated VR, and has also identified factors which need to be taken into account in the design of the virtual reality systems for the studies in this thesis.

In order to successfully create a toolkit for optimising VR for walking rehabilitation, a number of issues need to be addressed. Whilst some of them are outside the scope of this thesis, the following questions are investigated:

2.3.1 FACTORS FOR INVESTIGATION

i. There is evidence that the rate of optic flow can directly influence the speed of walking (section 2.2.3), but research to date only looks at very small timescales. **Can the modulating effects of optic flow on walking be sustained for several minutes (chapter 3)?**

ii. There is evidence that there is an altered perception of the speed of optic flow when treadmill walking in a virtual environment (section 2.2.3), which may reduce the usefulness of the optic flow modulations seen in chapter 3. However, it is not known whether there is a range of tolerance to changes in the optic flow/ walk speed ratio (visual gain). **Is there a range of tolerance for the perception of normal visual gain (chapter 4)?**

iii. If self motion perception can be improved it may widen the potential applications of optic flow modulation. Visual clutter may influence self-motion perception (section 2.2.2.1), but it is not known if this is due to the increase in visual cues, or the presence of virtual obstacles. **Does visual clutter influence self-motion perception in the absence of virtual obstacles (chapter 4)?**

iv. In settings where optic flow modulation is not appropriate due to the perceptual conflict with self-motion, other factors need to be considered to facilitate faster walking. Studies in non-VR settings indicate significant effects of audio on walking (section 2.2.2.2), but it is not known whether this effect would be present during self-paced treadmill walking or in VR. **Does audio cue tempo influence walking speed during self-paced treadmill walking with and without VR (chapters 5 and 7)?**

v. The treadmill input device itself may influence movement (section 2.2.1.3), potentially reducing the benefits seen using optic flow modulations and audio cues. However, there is a lack of data comparing overground walking with self-paced treadmill walking to, and therefore it is not known whether the apparent differences are real or due to population sampling. **Is there a difference in walking overground compared with self-paced treadmill walking (chapter 6)?**

2.3.2 FACTORS FOR STUDY DESIGN

I. The presence of peripheral visual cues may improve the accuracy of self-motion perception (section 2.2.2.1), therefore the studies in this thesis have been designed using virtual scenes with peripheral visual cues such as hallway walls or pillars (Chapters 3-7).

II. A higher level of visual contrast in the scene may improve self-motion perception (section 2.2.2.1), therefore the studies in this thesis have been designed using virtual scenes with a high level of contrast (Chapters 3-7).

III. The dimensions of objects in the virtual environment are likely to influence perceived movement speeds (section 2.2.3). Therefore the virtual environments used in the studies for this thesis have been calibrated to real-world dimensions (Chapters 3-7).

IV. Previous studies have indicated that a wider field of view may improve the accuracy of self-movement perception (section 2.2.4.2). Therefore the studies in this thesis have been designed using large screen displays with a wide field of view (chapters 3-7).

V. There is some evidence that stereoscopic projection improves depth perception, and also that induction of self-motion perception is stronger in stereoscopic VR than in monoscopic VR (section 2.2.4.3), and therefore the studies in this thesis have been designed to use stereoscopic displays wherever possible (chapters 3-5).

VI. There seems to be little difference between the use of speakers and headphones with respect to movement and movement perception VR, but headphones prevent intrusion of extrinsic noise during experiments (section 2.2.2.4), therefore headphones will be used to deliver the audio components of the studies in this thesis (chapters 5 and 7).

3. INVESTIGATION OF THE SUSTAINED EFFECT OF OPTIC FLOW ON TREADMILL WALK SPEED

3.1 SENSORY CONTROL OF HUMAN WALKING

Human walking is controlled using complex cognitive and sensory information. A variety of sensory inputs are integrated and processed, resulting in stimulation of the appropriate muscular effectors to carry out the desired movement. There are a number of factors which influence walking (Dietz, 2002), but the three main sensory contributions are:

1. The visual system detects changes in size and position of objects on the retina and this 'optic flow' can be used to determine the relative movement of different objects, in order to discriminate between movement of objects in the environment, and movement of self (Gu, Angelaki, & DeAngelis, 2008).

2. The vestibular system (in the inner ear) detects accelerations, and therefore contributes most significantly to motion data during active and passive changes of velocity or direction (Angelaki & Cullen, 2008).

3. The joint and muscle proprioceptive apparatus gives feedback relating to the static and dynamic status of the musculoskeletal system, and therefore contributes most significantly to motion data during active body movement (Dietz, 2002).

During normal walking, in a stable overground environment, the sensory information from these sources is congruent. It thus provides continual feedback and enables accurate updating of biomechanical output. However, situations often arise where these cues are in conflict and additional processing is then required to disambiguate the conflicting signals to obtain a rational construct of self- and world-motion.

For example, climbing a sliding sand-dune provides proprioceptive cues of steady forward movement and visual and vestibular cues of alternating forward and backward movement. Slipping on ice or a wet floor gives visual and vestibular cues of motion, but proprioceptive cues suggest standing balance. Similarly, sitting on a train in a station can give strong visual cues of self-motion as an adjacent train pulls away, but vestibular and proprioceptive cues suggest static posture. In situations such as these, it is necessary to adjust the relative weightings given to the sensory inputs in order to disambiguate these signals.

Harris, Jenkin and Zikovitz (2000) attempted to separate out the contributions of visual and vestibular input in travel distance judgments by using either blindfolded physical movement or passive visual movement to estimate travel distances to a target, and found that when conflicting visual and vestibular cues were available, the information from the vestibular cues was dominant. However, this study used constant acceleration, which is rarely seen in human locomotion. Therefore the findings cannot be generalised to include normal walking, with its periods of varying accelerations in addition to periods of constant velocity.

Similarly, Sun, Lee, Campos, Chan and Zhang (2003) conducted a series of studies to evaluate the relative contributions of visual and proprioceptive input on self-speed estimation. Using a stationary bike, and optic flow (OF) delivered via a head-mounted display (HMD), they provided combinations of proprioceptive and visual speed information and measured the effect of conflicting cues on speed estimation. They found that proprioceptive input was dominant in speed estimation, with only 21% of the speed estimates being attributable to the OF component. However, the authors point out that the participants had to attend carefully to pedalling speed and this may have biased the attention towards the physical rather than visual motion. In addition, the pedalling rate is a strong temporal speed cue and this is also likely to have biased the speed judgements towards the physical rather than visual cues. Nevertheless, the results seem to support Harris' observation that the visual cues are not dominant when in conflict with other sensory input. In addition, it is known that people are inaccurate in estimating distances (Sharrack & Hughes, 1997), and since speed is a function of distance and time, there is likely to be an inherent tendency to error when visually estimating speed.

However, it is clear that the visual input still has a notable effect on self-motion perception, and it has been observed by a number of researchers that manipulation of the optic flow can lead to visuomotor recalibration, altering the rate or direction of self-motion (e.g. Durgin, *et al*., 2005; Konczak, 1994; Mohler, *et al*., 2004; Pailhous, *et al*., 1990; Prokop, *et al*., 1997; Warren *et al*., 2001). It is this observation which is of particular interest with regards to walking rehabilitation, as optic flow is relatively easily manipulated within VR and therefore has the potential to be exploited to facilitate rehabilitation within virtual reality.

3.2 THE PERCEPTION AND INFLUENCE OF OPTIC FLOW DURING WALKING

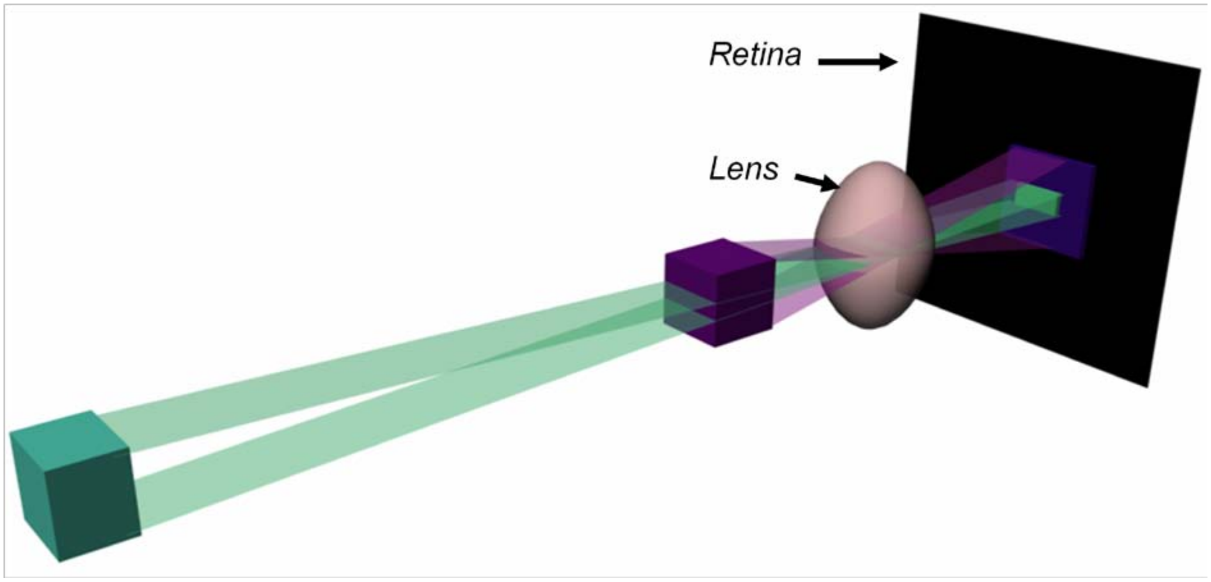

FIGURE 3.1: THE DISTANCE-RELATED CHANGES OF CUBE SIZE AS REPRESENTED ON THE RETINA

The image of an object on the retina enlarges as it comes nearer and shrinks as it moves away (Figure 3.1), and this 'optic flow' phenomenon is used as a visual cue to assess both speed of movement and direction (M. Harris, 2002).

Whilst the observer is stationary, changes of object size and position on the retina can be confidently attributed to object movement. However, when the observer is in motion, self-movement needs to be subtracted from relative object movement to identify the component attributable to object movement. The visual system can thus be used to discriminate between movement of objects in the environment, and movement of self (M. Harris, 2002).

Duffy (1998) carried out a series of studies on monkeys using combinations of visual and physical motion, and suggested that it is input from the vestibular system that is used to resolve ambiguities in optic flow. He recorded the responses of neurons in the Medial Superior Temporal (MST) region of the brain, and observed that some of the MST neurons respond to optic flow without vestibular input, whereas others respond to a combination of visual and vestibular input, suggesting that it may be here that self-movement and object-movement is disambiguated. However, in some circumstances, such as the example of a train pulling out of a station, a strong sense of vection (self-motion) can be engendered without any vestibular input. This suggests that in some circumstances, optic flow alone can be interpreted as self-motion.

Warren and Rushton (2007) demonstrated that, in the absence of extra-retinal information (i.e. non-visual information), global retinal motion patterns can be identified that enable the retinal motion due to self-movement to be subtracted from the total retinal flow. Thus, in normal circumstances, self-motion can be reliably estimated from global optic flow. This could explain induction of vection. For example, in the train example, the moving train produces a high level of optic flow, which may be interpreted as global motion (it appears that the entire external environment is moving relative to the individual, which is normally interpreted as self-motion). Thus, when there is conflicting input from more than one source regarding self-motion, the visual information does not always appear to be overridden by the conflicting sensory cue(s).

One of the first studies into this phenomenon projected a moving pattern onto the floor and walls of a large room, and observed participants attempting to maintain a constant walking velocity whilst a forward or backward flow of the moving pattern was presented (Pailhous, *et al*., 1990). Although only very short walk distances were recorded (around 6m), nevertheless it was observed that changes in optic flow caused significant modulations of gait.

Another early study, using a moving room to create optic flow conflicts during walking (Konczak, 1994), found that faster optic flow decreased walking speed, and slower optic flow increased walking speed. It was suggested that the participants were attempting to adjust the walking speed to achieve a visually 'normal' optic flow, although the modulations in walking speed were relatively modest and measured over short time scales. Also at no point did the participants attempt to walk backwards to 'match' the optic flow when it was presented in the opposite direction. However, Prokop *et al*. (1997) disagree with Konczak's suggestion, and propose a different mechanism for the modulating effect of optic flow on walk speed. They conducted a study using a closed-loop self-paced treadmill linked to the optic flow of a virtual corridor, and sinusoidally varied the relative optic flow from -1 (flow at walking speed incongruent with direction of walking) to 3 (flow at 3 times the walk speed congruent with direction of walking). Again it was noted that slow optic flow increased walking speed, and fast optic flow decreased walking speed. An inverse linear relationship between optic flow and walking speed was observed, with walking speed decreasing as optic flow speed increased, and vice versa. The walking speed changes were primarily achieved by changes in step length, with cadence (step frequency) remaining relatively constant. They suggest that, rather than attempting to match the optic flow, participants are responding to the mismatch between the proprioceptive and visual cues by responding to the relative weightings given to the cues.

Step length is a spatial characteristic and thus arguably more likely to be influenced by visual feedback, whereas cadence is a temporal characteristic of gait, mediated by proprioceptive feedback at a spinal level (Figure 3.2) (e.g. MacDougall & Moore, 2005).

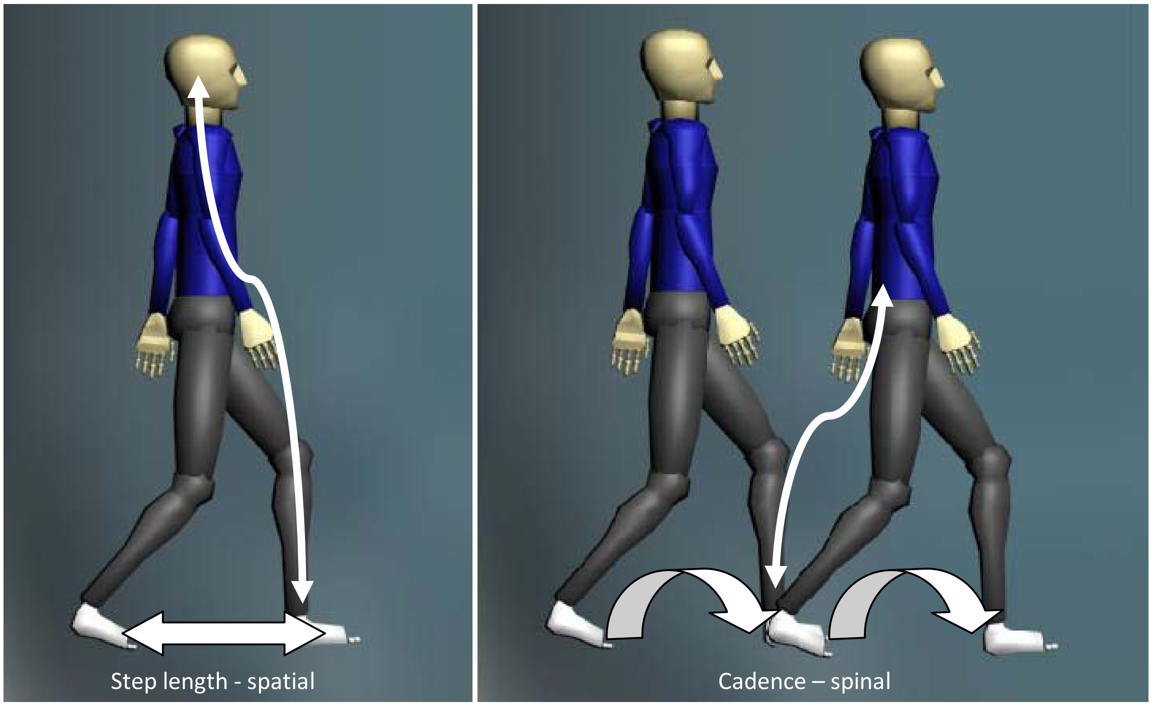

FIGURE 3.2: DIFFERENTIAL SENSORY CONTROL OF STEP LENGTH AND CADENCE

A more recent study by Prokop's team included patients with Parkinson's Disease as well as healthy participants (Schubert *et al.*, 2005), and again they found an inverse linear relationship between optic flow and walk speed, with the Parkinson's Disease participants showing a much greater response than the healthy participants. This supports the earlier suggestion that the magnitude of the walk speed variations reflects the relative weightings given to the proprioceptive and visual inputs. Patients with Parkinson's Disease have a reduction in the ability to respond appropriately to proprioceptive signals (Valkovič, Krafczyk, šaling, Benetin, & Bötzel, 2006), and may well have a greater dominance of the visual control of movement, giving a greater weighting to the optic flow cues and hence a greater influence on walk speed. Alternatively, it could be postulated that the Parkinson's patients have a lower baseline walk speed and therefore more potential for walk speed increases with slow optic flow, but this would not explain the finding that they also have a greater (slowing) response to the faster optic flow cues. Further work is needed in this area to establish the cause of these differences, although this is outside the scope of this thesis.

Studies of the effect of optic flow changes on gait to date have concentrated on optic flow modulations over short time scales, typically of a few seconds duration (e.g. Konczak, 1994; Pailhous, *et al*., 1990). However, if there is to be a practical application for rehabilitation or training (sections 1.3 and 2.1) then the effect needs to be sustained for longer time periods. Although it might appear that the studies by Prokop *et al*. (1997) and Schubert *et al*. (2005) involved longer walking durations, in fact the optic flow was being continuously modulated during the 8 minute walk cycle, and participants only walked for about 15 seconds for each unit change of relative optic flow. Furthermore, Prokop (1997) suggested that there may be an attenuation of the modulating effect of optic flow over time. They repeated 4 cycles of the optic flow modulation across 8 minutes, and noted that the changes in walk speed on the later cycles were smaller than those seen on the first cycle. He suggested that this may be due to an increase in the weighting of the proprioceptive component over time. However, this attenuation was seen in response to constantly changing ratios between the visual and proprioceptive sensory information. Exposure to a consistent ratio of visual/proprioceptive conflict may give rise to a recalibration of motion cues (e.g. Durgin, *et al*., 2005), but in Prokop *et al*.'s study the visual component was not stable, and in this situation it is plausible that greater weighting would be given to the (more consistent) proprioceptive input, reducing the effect of the optic flow over time. It is possible therefore that given a consistent (non-varying) optic flow/proprioceptive ratio, the increased walk speed seen in previous studies may be maintained over time.

A number of studies have demonstrated that exposure to visual information that is incongruent with other sensory cues appears to give rise to changes in the integration of the signals, leading to a recalibration of movement. For example, Mohler *et al*. (2004) conducted a study in which participants walked on a treadmill for 10 minutes in a VR system which displayed a virtual hallway on a back-projected screen, with non-varying relative optic flow of 0.5, 1 or 2, and then walked blind to a previously viewed target. It was found that after being exposed to slow optic flow the participants overshot the target distance, and with fast optic flow they undershot the target distance. This was an interesting finding, as Mohler's participants were exposed to incongruent optic flow for considerably longer than those in Prokop's study, but clearly demonstrated an effect on subsequent movement, even after 10 minutes of continuous exposure. This suggests that not only can varying the relative optic flow give rise to a recalibration of movement, but that this recalibration may be sustained over time. Another study which focussed specifically on the effects of visuo-motor recalibration over time (Durgin *et al*., 2005) found that recalibration occurred within 20 seconds and saturates at around 1 min, with no further change in effect even after 8 min. Although this study was not using optic flow, but rather proprioceptive input from treadmill running, nevertheless it does suggest that movement recalibration may be sustained during prolonged exposure to conflicting sensory cues.

Although research to date has only demonstrated short-term modulations of walk speed in response to optic flow manipulation, evidence from other visuo-motor recalibration studies suggests that modulations may have an effect over longer time scales. Therefore an empirical study was conducted to determine whether the modulating effect on walking can be sustained for several minutes (section 2.3.1).

3.3 METHOD

Previous studies demonstrating the beneficial effects of treadmill training for walking rehabilitation are inconsistent in the training protocols used, and therefore it is difficult to ascertain the ideal duration for sustained fast walking speeds. Walking times range from 5 minute blocks (Sullivan, *et al.*, 2002) to 30 minutes total walking at undefined intervals (Ada, *et al.*, 2003), with other studies using very variable distance and time, and concentrating on increasing speed (Pohl, *et al.*, 2002).

Nevertheless, it is known that effective treadmill training for walking rehabilitation can be delivered in sessions of around 4-6 minutes (e.g. Laufer, Dickstein, Chefez, & Marcovitz, 2001), and therefore this study uses 5 minute blocks of treadmill walking for each of the optic flow conditions.

In a recent study that examined the sustained effects of manipulating optic flow on distance judgements ((Mohler, *et al.*, 2004), optic flow rates of 0.5, 1 and 2 times normal walk speed were found to be effective, and therefore these ratios were also used as a basis for this experiment, in order to establish whether the short term effects on walking speed would also be sustained over time.

The average overground walking speed for under 65's in the general population is 1.5 m/s (Knoblauch, Pietrucha, & Nitzburg, 1996), and so this speed was selected as the normal optic flow speed.

3.3.1 DESIGN

Hypothesis 1: Optic flow at a rate lower than normal walk speed will be associated with an increase in walk speed

Hypothesis 2: The effect of optic flow rate on walk speed will be maintained for the duration of the 5 minute trials

The average overground walk speed (1.5m/s) was set as the normal optic flow (condition B). Condition A was 0.5 times the speed of B, and condition C was twice the speed of B (Table 3.1).

TABLE 3.1: OPTIC FLOW RATES FOR THE EXPERIMENTAL CONDITIONS

Optic flow speed	**0.75m/s**	**1.5m/s**	**3.0m/s**	**No optic flow**
	condition A	condition B	condition C	condition D
Minute 1	A1	B1	C1	D1
Minute 2	A2	B2	C2	D2
Minute 3	A3	B3	C3	D3
Minute 4	A4	B4	C4	D4
Minute 5	A5	B5	C5	D5

A repeated measures (within subjects) design was used. Optic flow rate and time were the independent variables, and walk speed the dependent variable.

3.3.2 MATERIALS AND APPARATUS

It has been observed that optic flow tends to be perceived as slower in virtual reality (e.g. Durgin, *et al*., 2007), and it has also been demonstrated that higher contrast visual cues appear to move more quickly than those with lower contrast (Stone & Thompson, 1992), therefore a virtual scene with a high contrast monochrome walkway was created for this experiment (section 2.2.2.1). Furthermore, the influence of optic flow may be greater when the optic flow stimulus is similar in pattern to that encountered during everyday locomotion (Thurrell & Pelah, 2002). Since many real environments provide many peripheral vertical cues (buildings, trees, streetlamps etc), vertical pillars were added to the sides of the walkway (Figure 3.3).

Riecke *et al*. (2005) studied the effect of both HMD and back-projection screens on the perception of simulated ego-motion in virtual reality, and found that significant perceptual distortions occurred when using a head-mounted display (section 2.2.4.1). Therefore a

back projected display was chosen for this experiment. This also serves to reduce the risk of falling off the treadmill, as the view of the real world is not occluded (section 2.2.4.1).

Depth judgements in VR have been found to be more accurate using binocular disparity rather than shading or other monocular depth cues (Durgin, *et al.*, 1995), and so the virtual environment was displayed and viewed stereoscopically (section 2.2.4.3).

FIGURE 3.3: (A) PARTICIPANTS WALKED ON A SELF-DRIVEN TREADMILL IN FRONT OF A 4.5M WIDE DISPLAY. (B) THE VIRTUAL ENVIRONMENT SIMULATED MOVING ALONG A WALKWAY BETWEEN VERTICAL COLUMNS

The moving stereoscopic scene was projected onto the screen using a pair of Christie 7700 Lumen projectors with polarising filters. To minimise visual distraction, the room was darkened for the experiment, with the main light source being the display screen itself (Figure 3.3).

Field of view (fov) is also considered to be an important factor in perception of optic flow, with a narrow fov reducing lamellar flow (Banton, *et al.*, 2005), and therefore this experimental setup was designed to provide a horizontal fov of around 100^{o} (section 2.2.4.2). This was achieved by centring a self-driven treadmill 2m in front of a 4.5m x 2m display screen.

To record walk speed, two equidistant reflective markers were placed on the treadmill belt (104 cm apart). Each trial was recorded using a small video camera mounted behind the treadmill, with a local light source focussed on the treadmill belt to highlight the reflective markers. The footage was recorded at a rate of 25 frames per second, and by noting the frame number each time a marker appeared it was possible to accurately calculate the speed of the treadmill belt (*post hoc*) and thus the walking speed of the participants. Mean walk speeds were calculated for each minute of the five minute trials.

A 3-dimensional animation of a moving walkway was created using 3D Studio Max and rendered into a stereoscopic format using Virtalis StereoWorks. It consisted of two parallel rows of vertical columns (5m apart) on either side of a 4m wide walkway (Figure 3.3).

The animation was rendered to run at 25 fps for five minutes at each of the 3 different optic flow speeds, all with optic flow direction congruent with the direction of normal walking (i.e. pillars appear to be moving towards the participant).

3.3.3 PARTICIPANTS

Nine healthy volunteers (5 males and 4 females) between the ages of 33 and 57 (mean age 45.6) participated in this experiment (Table 3.2). Ethical approval was obtained from the University of Portsmouth Department of Sports Science ethics committee. Participants were from the University of Portsmouth staff.

TABLE 3.2 DEMOGRAPHIC DETAILS OF PARTICIPANTS FOR OPTIC FLOW STUDY

Participant ID	Age	Gender
OF01	49	m
OF02	57	m
OF03	48	m
OF04	40	m
OF05	44	f
OF06	40	f
OF07	33	f
OF08	52	f
OF09	47	m

3.3.4 PROCEDURE

Prior to the task all participants gave their informed consent and were given the experimental instructions (Appendix D). They spent a few minutes familiarising themselves with the equipment and walking on the treadmill.

They each participated in all four conditions in counterbalanced order. Each test required the participants to walk on the treadmill for five minutes at a self-selected comfortable pace, with a five minute rest between each test. Participants were instructed to attempt to maintain the same pace throughout all the tests. During each test, participants wore ear-plugs to minimise the influence of external noise such as the treadmill belt. They also wore lightweight cardboard polarised glasses to enable stereoscopic viewing.

3.4 RESULTS

A mean walkspeed (m/s) was calculated for each minute of every trial (Table 3.3).

$$\frac{number\ of\ marker\ counts\ per\ min \times marker\ distance\ (1.04m)}{60s}$$

TABLE 3.3: MEAN WALK SPEED (M/S) FOR EACH MINUTE OF THE FOUR EXPERIMENTAL CONDITIONS

	Condition	**OF01**	**OF02**	**OF03**	**OF04**	**OF05**	**OF06**	**OF07**	**OF08**	**OF09**	***Mean***	***StDev***
Minute 1	**A**	0.96	0.75	0.68	1.01	0.75	0.85	1.11	1.18	1.25	*0.95*	*0.21*
	B	0.78	0.70	0.80	1.08	0.68	0.82	0.96	1.27	0.94	*0.89*	*0.19*
	C	0.78	0.64	0.73	0.89	0.57	0.70	0.96	1.24	1.01	*0.84*	*0.21*
	D	0.94	0.61	0.68	0.75	0.66	0.84	1.06	1.22	1.10	*0.87*	*0.22*
Minute 2	**A**	1.08	0.84	0.66	1.10	0.87	0.91	1.17	1.25	1.36	*1.03*	*0.22*
	B	0.87	0.77	0.78	1.15	0.71	0.87	0.92	1.27	1.05	*0.93*	*0.19*
	C	0.82	0.70	0.73	0.91	0.63	0.78	0.89	1.22	1.13	*0.87*	*0.20*
	D	1.03	0.64	0.64	0.80	0.71	0.87	1.10	1.27	1.25	*0.93*	*0.25*
Minute 3	**A**	1.11	0.85	0.73	1.13	0.99	0.91	1.11	1.25	1.36	*1.05*	*0.20*
	B	0.94	0.75	0.80	1.13	0.75	0.87	0.98	1.24	1.13	*0.95*	*0.18*
	C	0.89	0.68	0.68	0.94	0.66	0.82	0.94	1.22	1.10	*0.88*	*0.19*
	D	1.03	0.63	0.66	0.85	0.73	0.82	1.15	1.24	1.34	*0.94*	*0.26*
Minute 4	**A**	1.15	0.82	0.71	1.13	1.17	0.92	1.11	1.29	0.02	*0.93*	*0.39*
	B	1.05	0.75	0.75	1.17	0.75	0.91	0.99	1.22	0.02	*0.84*	*0.36*
	C	0.99	0.73	0.63	0.99	0.66	0.80	0.92	1.17	0.02	*0.77*	*0.33*
	D	1.05	0.66	0.70	0.89	0.82	0.85	1.15	1.29	0.02	*0.82*	*0.37*
Minute 5	**A**	1.18	0.84	0.70	1.17	1.31	0.94	1.11	1.27	1.38	*1.10*	*0.23*
	B	1.11	0.77	0.75	1.13	0.91	0.87	1.01	1.22	1.20	*1.00*	*0.18*
	C	0.99	0.73	0.66	1.05	0.78	0.78	0.92	1.20	1.17	*0.92*	*0.19*
	D	1.08	0.68	0.68	0.94	0.82	0.92	1.11	1.25	1.45	*0.99*	*0.26*
Total (5 mins)	**A**	1.10	0.82	0.70	1.11	1.02	0.91	1.13	1.25	1.35	*1.04*	*0.21*
	B	0.95	0.75	0.78	1.13	0.76	0.87	0.97	1.24	1.09	*0.95*	*0.18*
	C	0.90	0.70	0.69	0.95	0.66	0.78	0.93	1.21	1.10	*0.88*	*0.19*
	D	1.02	0.64	0.67	0.85	0.75	0.86	1.11	1.25	1.30	*0.94*	*0.24*

A repeated-measures 2-way ANOVA (optic flow speed x time) demonstrated a significant effect of optic flow ($F_{(3,24)}$=6.70 p<0.01), but no significant effect of time (F($_{4,32}$)=1.01 p=0.42).

Post-Hoc testing revealed that walk speed in the slow optic flow condition (A) was significantly faster than condition B (t(8)=2.35 p<0.05), and faster than condition C (t(8)=4.60 p<0.01) and also faster than condition D ((t(8)=2.99 p<0.05). Walk speed was also significantly slower in the fast optic flow condition (C) than in condition B (t(8)=3.81 p<0.01).

Walk speed was fastest in the slow optic flow condition, and slowest in the fast optic flow condition. This trend is consistent across each minute of the five 1-minute sub-trials for each condition.

However, the baseline walk speed was significantly lower than the anticipated speed of 1.5m/s (t(8)=6.91 p<0.001).

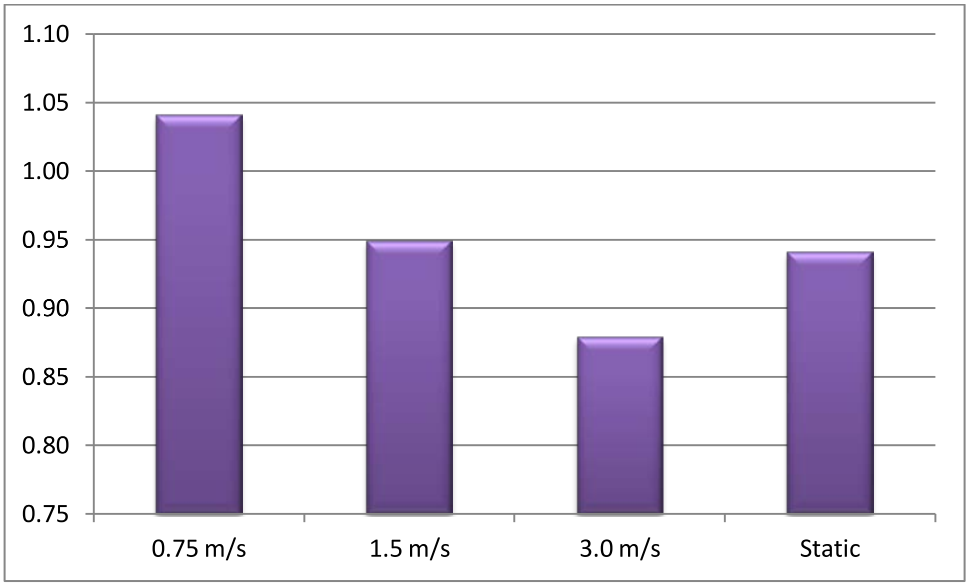

FIGURE 3.4: MEAN WALK SPEED (M/S) FOR EACH OF THE EXPERIMENTAL CONDITIONS

The mean walk speeds were 11% higher in the slow optic flow condition (0.75m/s) than in the static baseline. Conversely, walk speeds were 7% lower in the fast (3m/s) optic flow condition (Figure 3.4). However, the speeds were all slower than the average overground walk speed of 1.5 m/s.

In summary, the results support the hypothesis that slow optic flow is associated with faster walking speeds than the faster optic flow rates in this experimental setup, and also support the hypothesis that the effect of optic flow rate on walk speed is maintained for the duration of the five minute trials.

3.5 DISCUSSION

This experiment is the first to demonstrate that the modulating effect of optic flow can be sustained over 5 minutes.

The inverse linear relationship between optic flow and walking speed is similar to that found in previous studies (e.g. Konczak, 1994; Pailhous, *et al.*, 1990; Prokop, *et al.*, 1997; Schubert, *et al.*, 2005), supporting the suggestion that there is a visuo-motor feedback control that is able to make adjustments to self-motion in response to altered visual input. As in previous studies, it was noted that the magnitude of the changes in walk speed were not directly proportional to the changes in optic flow, supporting previous hypotheses that the sensory control of walking is multi-factorial, and that the visual input does not completely override the information from the other sensory cues (L. R. Harris, *et al.*, 2000; Sun, *et al.*, 2003).

The treadmill apparatus used in this experiment was self-driven, requiring physical effort from the participant to maintain the motion of the treadmill belt. As with similar types of treadmill, this is facilitated by a slight slope of the treadmill, giving the sensation of a low uphill gradient. However, the optic flow simulated level walking, and therefore may have created unintentional incongruence between the proprioceptive & vestibular signals, and the visual feedback. Walking uphill reduces the effective rate of horizontal lamellar (peripheral) flow, and thus might cause an expectation of somewhat lower optic flow. However, the participants were encouraged to direct their gaze forward and this would have provided a higher level of central optic flow, which is less affected by the gradient of the walking path. Indeed, the results showed a similar magnitude of effect to those using a level treadmill platform (Schubert, *et al.*, 2005), suggesting that the small treadmill gradient has little impact.

Although the experimental design based the optic flow speeds on multiples of ‘normal’ overground walking speed of 1.5m/s, the participants in this experiment walked on the treadmill at an average speed of 0.94 m/s (SD 0.24), which is similar to the steady walking speeds in previous treadmill studies (e.g. Varraine, *et al.*, 2002), and significantly slower than average overground walking speeds of 1.5 m/s. This might suggest a need for a slower optic flow (around 1m/s) for the matched condition (B), but previous studies have also suggested that optic flow needs to be increased, by as much as 50%, to seem normal to participants walking on a treadmill (Banton, Steve, Durgin, & Proffitt, 2000). The close matching of average walking speed in conditions B and D reported here supports this finding.

However, there is currently no research investigating the full range of optic flow which can be accepted as normal when treadmill-walking in VR, and further work is needed to establish the range of perception of normal optic flow, and what implications this might have for the use of optic flow manipulation in treadmill-mediated VR (chapter 4).

In addition, there have been no studies comparing overground walking with self-paced treadmill walking. Since it appears that self-paced treadmill walk speeds may be significantly lower than average overground walk speeds, this may have implications for the suitability of treadmills in VR for walking rehabilitation. Further investigation is therefore indicated to compare treadmill walking speeds with normal overground walking speeds (chapter 6).

These preliminary results suggest that decreasing the rate of optic flow during treadmill walking may cause a significant increase in walking speed. Although this experiment was carried out on healthy participants, incorporating this effect into a Virtual Environment, where optic flow is geared up or down via a treadmill-to-environment interface, could be used to enhance gait rehabilitation. However, further work is needed to assess the extent of the effect on clinical groups (chapter 7).

It is possible that low ratio (slow) optic flow speeds may be able to reduce the self-speed perception, and since fear of falling during faster walking may be a contributing factor preventing an increase in walking speed (Chamberlin, Fulwider, Sanders, & Medeiros, 2005), the reduced optic flow may also facilitate faster walking speeds via the reduction of anxiety. Although fear of falling was not addressed in this study of healthy adults, it warrants further investigation to establish whether slow optic flow does indeed decrease fear of falling in vulnerable populations, although it is outside the scope of this thesis.

3.6 CONCLUSION

During normal walking, multiple congruent sources of sensory information provide feedback on walking speed. Creating a conflict in the visual component of this feedback system (optic flow) can lead to a recalibration of motion (section 2.2.3). The findings of this experiment extend previous optic flow studies (Konczak, 1994; Pailhous, *et al.*, 1990; Prokop, *et al.*, 1997; Schubert, *et al.*, 2005) by demonstrating that the modulating effect of optic flow on walking speed can be sustained for several minutes, offering the potential for use in treadmill-mediated locomotor rehabilitation.

However, the lower overall treadmill walking speed raises the question of whether the benefits of optic flow manipulation can offset the slower walking speeds seen with the use of a treadmill interface.

Furthermore, since there is already known to be a misperception of optic flow speeds in VR (section 2.2.2.1), this may be compounded when slowing the optic flow to facilitate faster walking, and further study is required to establish the boundaries of the range of tolerance of changes in optic flow (chapter 4).

4. INVESTIGATION OF THE PERCEPTION OF NORMAL OPTIC FLOW IN TREADMILL-MEDIATED VIRTUAL REALITY

Walking speed can be manipulated by controlling the rate of optic flow in a treadmill-mediated virtual environment (chapter 3), and this may have potential for enhancing the recovery process for patients undergoing walking rehabilitation (section 3.5). However, it has also been suggested that increasing realism in virtual environments offers more ecological validity to the tasks performed in VR (e.g. Anton, Opris, Dobrean, David, & Rizzo, 2009; Loomis, Blascovich, & Beall, 1999), and it is possible that slowing the optic flow may decrease realism. As the optic flow rate is reduced, there will come a point at which the perceived visual progression through the virtual environment is noticeably incongruent with the perceived speed of self-motion.

Previous studies have observed that there is already an altered perception of the speed of optic flow when treadmill walking in a virtual environment (e.g. Distler, *et al*., 1998; Durgin, Gigone, *et al*., 2005). Therefore, if the optic flow in VR is altered to manipulate walking speed then it is important to understand how this may impact perceived realism. It is therefore necessary to identify the magnitude and direction of altered perception of optic flow, and its potential interplay with optic flow manipulation, in order to optimise the virtual rehabilitation experience (section 2.2.3).

4.1 VISUAL GAIN AND THE PERCEPTION OF OPTIC FLOW

It might be intuited that optic flow should have a direct relationship with walking speed for it to be perceived as correct (Figure 4.1). This would equate to a **visual gain** (optic flow/walking speed) of 1:1.

However, in virtual reality, the optic flow does not necessarily have to be matched to the walking speed, and thus the visual gain could be higher or lower than 1:1. Indeed, if optic flow is to be used to manipulate walking speed (chapter 3) then the visual gain would need to be lower than 1:1 (e.g. 0.75:1 section 3.4).

The challenge lies in identifying the correct optic flow speed for a given walking speed for the visual gain to be perceived as normal, and to establish whether the resulting visual gain is lower than 1:1 (useful for increasing walk speed) or higher than 1:1 (associated with slower walking).

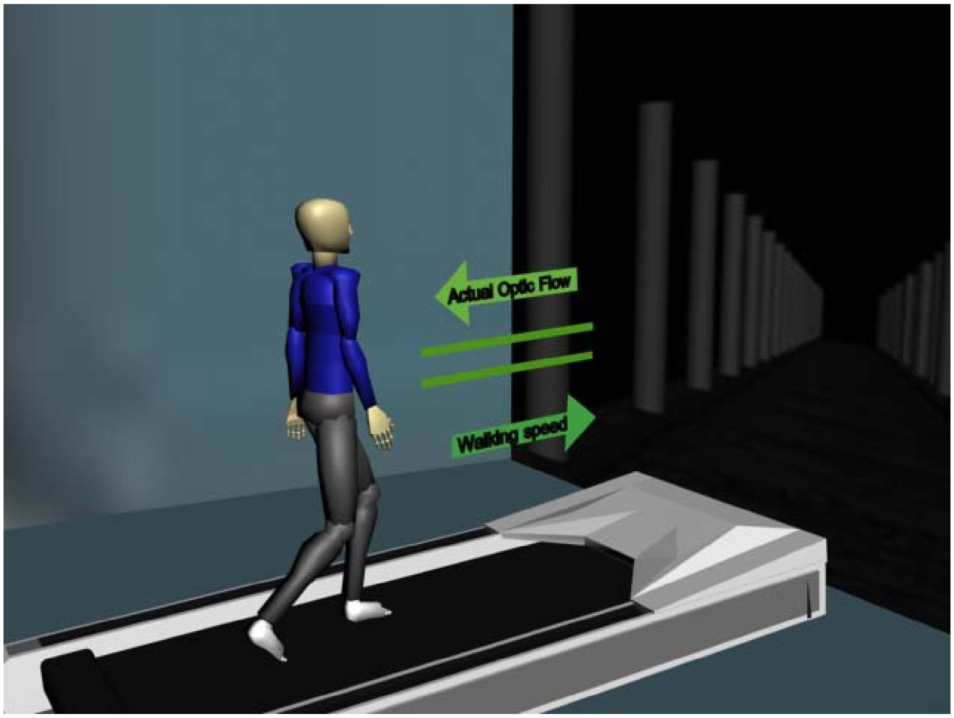

FIGURE 4.1: VISUAL GAIN IS 1:1 WHEN OPTIC FLOW AND WALKING SPEED ARE EQUAL AND OPPOSITE

According to the Motor Prediction Theory (Wolpert & Flanagan, 2001), the perceptual consequences of motor actions can be anticipated, and this prediction can be used to filter or cancel the sensory consequences of movement. For example, when walking at a known speed, the anticipated optic flow would be 'subtracted' from the actual optic flow, so that in a normal walking environment the surroundings would appear stationary. Durgin, Gigone and Scott (2005) undertook a series of experiments to investigate this theory, and the results predominantly supported the subtractive model. Interestingly though, they found that treadmill walking produced a lower level of **visual subtraction** than overground walking at similar speeds. If, as they propose, visual subtraction is related to self-speed, then this finding might suggest that walking on a treadmill gives a slower self-speed estimation. However, this is in direct contrast to the findings of Alton, Baldey, Caplan and Morrissey (1998), who observed that treadmill speeds were felt to be higher than the same overground speed. Durgin, Gigone and Scott (2005) suggest that the lack of physical forward motion may be contributing to the lower levels of visual subtraction during treadmill walking, and this does seem to be supported by their finding that the visual subtraction during overground walking is approximately equal to the sum of the visual subtractions for treadmill walking and for passive forward movement. If this is the case, then there are perhaps different mechanisms used for self-speed estimation and for optic flow prediction, with motor prediction contributing to visual subtraction but not accounting entirely for the phenomenon.

The findings of a follow-up study (Durgin, *et al*., 2005) do suggest other mechanisms that may also contribute to the perception of visual speed, including the effect of adding clutter to a virtual environment on the matching of visual and motor estimates of the speed of self-motion ("**gain matching**"). Their results suggested that the more cluttered environment significantly improves visual gain matching in overground walking, but not during treadmill walking. They suggested that the cluttered environment may not simply be providing an increase in the visual cues for improved depth perception, but rather that they may represent obstacles to be avoided. They postulate that in the overground condition an obstacle avoidance mechanism would be activated, which may improve the accuracy of speed estimation. Since the participants walking on the treadmill were holding static handrails throughout the trials, tactile feedback may have reduced the need to use a visual-based avoidance system.

Whilst this theory may have some merit, the experimental design makes it difficult to directly compare the two conditions. The overground tests accelerated from standing for each trial, whilst the treadmill trials involved continuous motion. In addition, the walking speed overground was variable and controlled by the participant, and could be as low as 1.1m/s. However, speed on the treadmill was fixed at 1.34m/s, and it has previously been suggested that the walking speed of the participant can affect the accuracy of visual gain matching (T. Banton, *et al*., 2005). Thus this may have been a factor in the difference between the two walking conditions.

In an attempt to address some of these issues, Durgin, Reed and Tigue (2007) undertook a further series of studies investigating the phenomenon of gain matching during treadmill walking. They note that the previous work on visual subtraction discrepancies when treadmill walking only account for around 15% of the error, but gain matching errors are generally found to be considerably higher than this (e.g. Banton, *et al*., 2005; Durgin, *et al*., 2005; Durgin, Gigone, *et al*., 2005). Thus there must be some other factor which is contributing to the gain matching errors.

The **walk ratio** (step length/cadence) is remarkably constant for an individual (Sekiya & Nagasaki, 1998), but treadmill walking is associated with a higher step frequency relative to step length, i.e. a lower walk ratio (e.g. Alton, *et al*., 1998; Stolze, *et al*., 1997).

Durgin postulates that self- speed estimates may be based on step frequency, and thus the 10% decrease in walk ratio seen in treadmill walking would be perceived as a 10% increase in speed (Durgin, *et al*., 2007). Indeed, their study did find that visual gain could be accounted for by combining the walk ratio decrease with the 15% error in visual subtraction.

The visual gain seen in Durgin *et al*.'s study is in fact somewhat lower that those observed in the earlier studies, and the authors attribute this to the closer link between perception and action in their improved treadmill apparatus. However, although they allowed each trial to accelerate from stationary to prevent a visual standard being established, the treadmill speed was still not under the control of the participant, and thus the results are still not reliably comparable to normal overground walking. In addition, each trial consisted of a 1 second ramp-up from stationary and then 4 seconds walking at the target speed, so 20% of each trial was actually during the acceleration phase, which may have affected speed judgments.

In an extension of previous work, using higher fidelity treadmill apparatus (Durgin, *et al*., 2007), it was again found that the more cluttered virtual environment was associated with more accurate gain matching in both overground and treadmill walking, but it is not really clear whether this was due to more accurate speed perception, or because the addition of objects closer together in near space artificially increase the number of visual cues available to estimate optic flow. A further study comparing static (non-walking) speed estimation of the empty and cluttered hallways would be necessary to establish this.

Whilst there is some disagreement as to the absolute value of gain mismatch when treadmill walking in VR, it is clear that all these studies identify gain matching errors in the same direction, i.e. visual speeds are perceived as slower than they actually are. This does indicate that for treadmill-mediated VR to appear ideal to a user, a visual gain >1:1 should be used when setting the visual gain between the treadmill and the environment. However, the previous studies have all attempted to quantify the ideal normal visual gain value, without establishing whether there is a range of which may be considered to be normal. Since a visual gain <1:1 is desirable to facilitate faster walking (chapter 3), it is important to know whether this visual gain would be accepted within the range of normal visual gain perception.

Therefore, whilst previous studies, using the **staircase method** of psychophysical evaluation, have been able to identify a perceived "most normal" visual gain, it may be more useful to identify what is the perceived "tolerance of normal". In each of the studies above, the participants were given the option of identifying 'fast' or 'slow' in response to the changing optic flow speeds. This method is suitable for determining a perceptual boundary, but it is less able to identify a range of acceptable tolerance.

A recent study focused on a rating of "matched" rather than fast or slow (Kassler, *et al*., 2010), using a treadmill-mounted dial to allow users to adjust the optic flow multiplier until the visual gain was perceived to be normally matched. Whilst this study used a different approach to quantify the optimum normal visual gain setting, it still aimed to define a single value for this perceived matched visual gain.

It has previously been observed that people are not sensitive to visual gain changes of less than 15% (Kearns, Durgin, & Warren, 2002). Indeed, in one study a 50% change of simulated self-motion was required for a change to be perceived (Monen & Brenner, 1994), although this study used expanding flow fields rather than immersive VR, and this may account for the lowered ability to detect changes. Furthermore, it is not known whether different visual gains may be rated as normal even when they are perceptually different from each other (i.e a difference is perceivable but tolerable).

If there is a tolerance range in the perception of normal visual gain, then treadmill-mediated VR which is designed to operate within this range of visual gain may be less likely to cause visuo-motor dissonance. However, although the deviation from the mean (standard deviation) in previous studies may indicate a level of difficulty in identifying a single normal visual gain, this is most likely to represent the limits of perception of visual gain change, which is not necessarily equivalent to the limits of tolerance of visual gain change.

For example, in one study the visual gains were started at 0.61:1, 1:1 and 1.63:1, and then stepped up or down depending on the visual judgment of the participant (lower gain if the participant felt it was too fast, and higher gain if they felt it was too slow) (Durgin, *et al*., 2007). It is quite conceivable that the visual gain of 1.63:1 may have been perceived in the higher end of perceptually normal, but given the forced choice option between responding 'slow' or 'fast', the response of 'fast' is more likely to be chosen.

Likewise, the visual gain of 0.61:1 may have fallen into the lower range of perceptually normal, but in this case the forced choice response 'slow' would be required. It is not possible to establish the true range of normal visual gain tolerance without an experimental design that allows for both an upper and lower boundary of normal to be established.

This is not just an interesting theoretical point, but of fundamental importance to the design of virtual environments for walking rehabilitation. If the true range of perceived normal visual gain includes visual gains below 1:1, then it would be possible to exploit the benefits of lowered optic flow (Chapter 3) without decreasing perceptual realism. If, however, the perceptual visual gain is significantly higher than 1:1, then manipulating optic flow will involve a trade-off between therapeutic effect and perceptual realism. Therefore an empirical study was conducted to determine whether there is a range of tolerance for the perception of normal visual gain, and whether visual clutter influences self-motion perception on the absence of virtual obstacles (section 2.3.1).

4.2 METHOD

This experiment investigates whether the perception of normal visual gain during treadmill walking is at a single boundary, or whether acceptable normal visual gain falls within a range of tolerance for an individual. It aims to identify the upper and lower boundary of these values, and also investigates whether increasing visual clutter in a scene affects the perception of normal visual gain.

In Durgin's studies, visual gains ranging from 0.61:1 to 1.63:1 were used as starting points (Durgin, *et al*., 2007). However, the distributions in Kassler *et al*.'s study suggest that visual gains may be rated as normal across a much wider range than this (Kassler, *et al*., 2010). Therefore this experiment uses visual gains from 0.2:1 (just perceptible motion) up to 3:1 (just above the highest normal value found for an individual in Kassler *et al*.'s (2010) study).

It is possible that alerting participants to each visual gain change may not elicit the same results as allowing them to report perceived changes. Therefore in this experiment the different visual gains were further divided and presented in two different modes, automatic and prompted. In the 'prompted' mode, the visual gain was only changed after the participants gave a verbal judgement of the current visual speed. In the 'automatic' mode, the visual gain was gradually changed regardless of any feedback from the participant.

Durgin *et al*, (2005) found that visual clutter in an environment improved the accuracy of visual gain perception, but they did not know if this was due to an increase in the visual cues or the addition of obstacles to be avoided (section 2.2.2.1). Therefore in this experiment two different virtual environments were used. One had a monochrome walkway with virtual pillars spaced 5m apart, and no other visual distractions. The other scene had bright textures and detail applied to walls, floor and ceiling (Figure 4.4). In this way there was a large difference in the quantity and frequency of visual cues, but no difference in the presence of virtual obstacles. Both environments were designed to provide high contrast visual cues, and were back projected with stereo projection and a wide field of view, as detailed in section 3.3.2.

4.2.1 DESIGN

Hypothesis 1: The mean visual gain identified as perceptually normal is significantly greater than 1:1 (c.f. Distler, *et al*., 1998; F. H. Durgin, K. Gigone, *et al*., 2005).

Hypothesis 2: The minimum and maximum perceived normal visual gain values are significantly different from each other.

Hypothesis 3: The mean and range of perceptible normal visual gains are significantly different between the prompted and automatic presentation methods.

Hypothesis 4: Perception of normal visual gain will be more accurate in the visually cluttered scene compared with the less cluttered scene.

A within-subjects multi-factorial design was used (Table 4.1). Visual gain, environment type and visual gain presentation method were the independent variables, and perceived visual speed was the dependent variable.

TABLE 4.1: THE COMBINATION OF SCENE TYPE AND VISUAL GAIN CHANGE METHOD USED IN THE EXPERIMENTAL CONDITIONS

	Automatic visual gain change	**Prompted visual gain change**
Low visual clutter	condition A (Visual gain 0.2:1 – 3:1)	condition B (Visual gain 0.2:1 – 3:1)
High visual clutter	condition C (Visual gain 0.2:1 – 3:1)	condition D (Visual gain 0.2:1 – 3:1)

4.2.2 MATERIALS AND APPARATUS

Previous studies have used fixed treadmill speeds, but this places a constraint on the walking speed of the participants. Since Durgin *et al*. (2007)) found no significant difference in gain matching between 3 fixed walking speeds, it is likely that unconstrained walk speeds should elicit similar results. Therefore, to allow for natural walking, an adapted motorised treadmill was used. The manual controls were removed and replaced with a separate control system connected to a potentiometer (Figure 4.2).

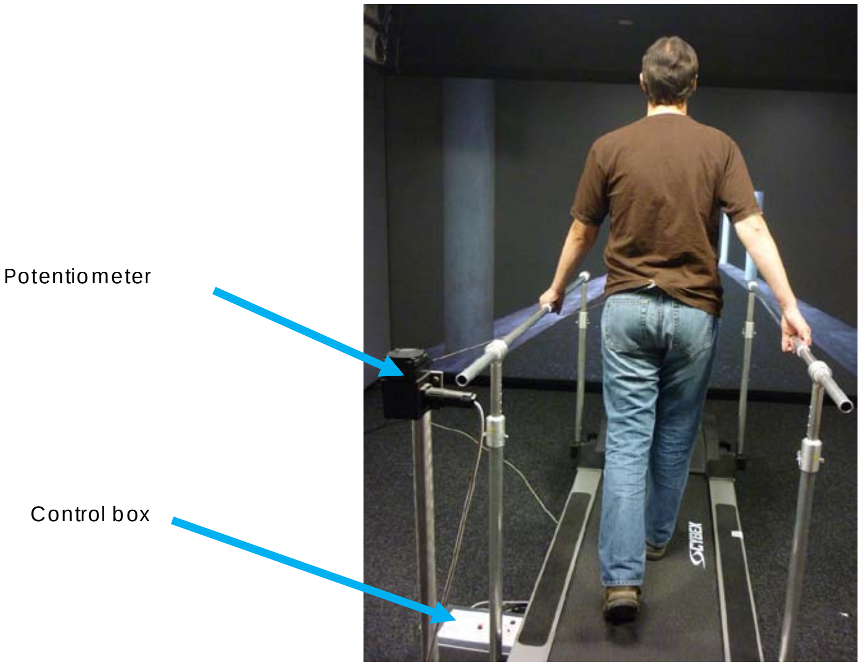

FIGURE 4.2: SELF-PACED TREADMILL WITH MOTOR CONTRLLED VIA POTENTIOMETER

The potentiometer detected the rate of change of position of the participant on the treadmill belt and thus was able to set the treadmill speed dynamically to the self-selected pace of the participant, by keeping them centred on the belt. This treadmill control system was similar to that described in more depth by Fung *et al*. (2006).

The treadmill also had handrails with sliding handgrips (Figure 4.3) to allow free arm movement whilst providing stability if required.

FIGURE 4.3: SLIDING HANDRAILS ALLOW NATURAL FREE MOVEMENT OF THE ARMS WHILST STILL PROVIDING STABILITY

The speed of the treadmill belt was monitored using an optical sensor. This input was processed using a bespoke C++ algorithm (Appendix A) and used to update the virtual camera view in real-time. This speed was updated every frame (30fps) at a resolution of 0.01 m/s.

Field of view (fov) is considered to be an important factor in perception of optic flow speed, with a narrow fov reducing lamellar flow (Banton, *et al.*, 2005), and therefore this experimental setup was designed to provide a horizontal fov of around 100° (section 2.2.4.2). This was achieved by centring the treadmill 2m in front of a 4.5m x 2m display screen.

Two different virtual scenes were used for the experiment in order to determine the effect of visual clutter (section 2.2.2.1). One scene consisted of two parallel rows of vertical columns on either side of a walkway, and the other was a brightly textured coloured corridor to provide visual clutter (Figure 4.4).

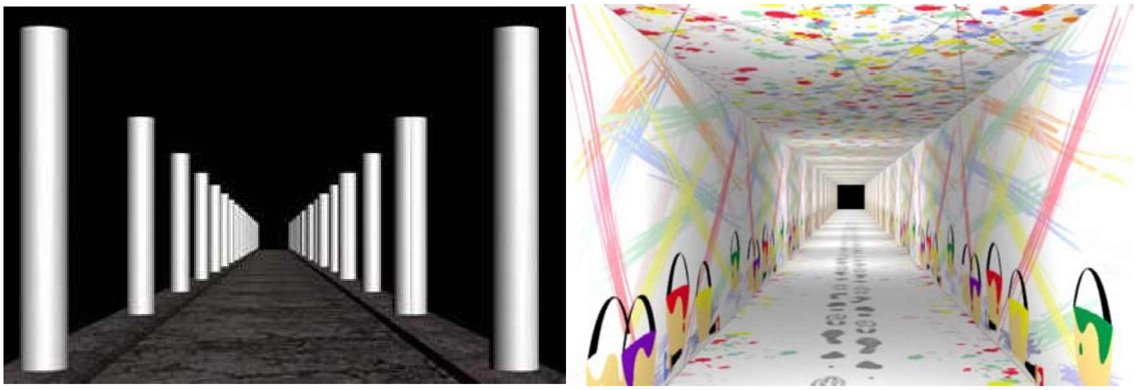

FIGURE 4.4: LOW AND HIGH VISUAL CLUTTER SCENES

Both scenes were created as 3-dimensional models using 3D Studio Max and rendered into an interactive format using Open Scene Graph. The virtual camera was set to match the starting position of the participant, with a fov of 100° and a height of 1.6m above the ground plane. The interactive stereoscopic scene was projected onto the screen using a pair of Christie 7700 Lumen projectors with polarising filters. To minimise visual distraction, the room was darkened for the experiment, with the main light source being the display screen itself.

The virtual scenes were linked to the treadmill via a software 'gearing' system, which enable precise control of the visual gain in the scene relative to the rate of treadmill walking (Appendix B).

Depth judgements in VR have been found to be more accurate using binocular disparity rather than shading or other monocular depth cues (Durgin, *et al.*, 1995), and so the virtual environments were displayed and viewed stereoscopically (section 2.2.4.3).

4.2.3 PARTICIPANTS

Twenty healthy volunteers from the University of Portsmouth staff and students (11 male, 9 female) between the ages of 19 and 55 (mean age 33.2) participated in this experiment (Table 4.2). Ethical approval was obtained from the University of Portsmouth School of Creative Technologies ethics committee.

TABLE 4.2: DEMOGRAPHIC DETAILS OF PARTICIPANTS FOR GAIN MATCHING STUDY

ID	Age	Gender	Regular computer game play?
GM101	32	F	Y
GM102	33	M	Y
GM103	25	F	N
GM104	38	F	N
GM105	29	F	N
GM106	19	M	Y
GM107	22	F	N
GM108	41	M	N
GM109	53	M	N
GM110	28	M	N
GM111	39	F	N
GM112	52	M	Y
GM113	28	M	N
GM114	28	M	N
GM115	22	M	Y
GM116	39	F	N
GM117	55	M	Y
GM118	24	F	N
GM119	33	M	N
GM120	23	F	N

4.2.4 PROCEDURE

Prior to the task all participants gave their informed consent and were given the experimental instructions (Appendix E).

The participants spent a few minutes familiarising themselves with the equipment and walking on the treadmill. Trials were not initiated until the participant was able to maintain a steady comfortable walking pace on the adapted treadmill. They were then familiarised with the experimental task using a demo program which presented very fast (3:1), normal (1:1) and very slow (0.2:1) visual gains.

In each condition the participants were presented with 30 visual gain changes, ranging from 0.2:1 (10m of treadmill walking moves the virtual camera 2m in the virtual environment) to 3:1 (10m of treadmill walking moves the virtual camera 30m in the virtual environment). Each trial started at a visual gain of 0.2:1 and increased by 0.2 at each gain change. Once a visual gain of 3:1 was reached, the visual gain was decreased by 0.2 at each change until it returned to 0.2:1.

In the 'prompted' mode, the participants gave a verbal judgement of the on-screen speed after each gain change:

“Slow” (on-screen movement appears too slow)

“Normal” (on-screen movement appears to match walking speed)

“Fast” (on-screen movement appears too fast)

The visual gain changes were initiated by the recording of the previous response, so the participants were in control of how long they needed to make a perceptual judgement. Each condition (30 trials) took approximately 3-5 minutes to complete.

In the 'automatic' mode, participants were instructed to report their verbal judgement of the on-screen starting speed, and then to report any time they noticed that the relative speed had changed (for example, from slow to normal, or from fast to slow etc).

Participants walked in each of the experimental conditions in counterbalanced order. For each condition the participants started to walk on the treadmill in front of a static image of the test scene. When the participant reported that they were walking comfortably, the treadmill movement was interactively linked to the scene via the gearing software. The participants were able to walk at any speed, with the treadmill control system dynamically updating the belt speed in response to walking speed changes.

Throughout the tests the participants wore lightweight cardboard polarised glasses to enable stereoscopic viewing

4.3 RESULTS

All descriptive and statistical analysis was carried out in PASW statistics 18.

For each trial, a weighted mean value was calculated for the visual gain values which were reported as appearing 'normal'. The minimum and maximum visual gain perceived as normal were also identified (Table 4.3).

TABLE 4.3: INDIVIDUAL WEIGHTED MEAN GAIN VALUES PERCIEVED AS NORMAL IN EACH CONDITION

ID	Mean				Minimum				Maximum			
	A	B	C	D	A	B	C	D	A	B	C	D
GM101	2.10	2.20	2.06	1.97	1.40	1.40	1.40	1.20	2.80	3.00	3.00	3.00
GM102	1.90	2.50	2.00	1.87	1.60	2.00	1.40	1.00	2.20	3.00	2.60	2.80
GM103	*	1.92	*	2.20	*	1.40	*	2.00	*	2.80	*	2.40
GM104	2.13	1.54	1.73	1.90	1.60	0.80	0.60	0.80	3.00	2.60	2.80	3.00
GM105	1.97	1.70	1.68	1.70	1.20	0.80	0.80	0.80	3.00	2.60	2.80	2.60
GM106	1.60	1.40	1.90	1.55	1.40	1.20	1.80	1.00	1.80	1.60	2.00	2.60
GM107	2.23	1.77	1.60	1.48	1.60	0.80	1.20	1.00	3.00	3.00	2.00	2.00
GM108	1.40	1.57	1.80	1.43	0.80	1.00	0.80	0.60	2.60	2.40	3.00	2.20
GM109	2.80	1.20	1.40	1.47	2.60	1.00	0.80	1.20	3.00	1.40	2.00	1.80
GM110	1.20	1.91	1.90	1.80	0.80	1.20	1.40	0.80	1.60	2.60	2.40	3.00
GM111	1.60	1.60	1.50	1.60	1.20	1.20	1.40	1.60	2.00	2.00	1.60	1.60
GM112	2.50	1.70	1.70	1.50	2.40	1.60	1.40	1.40	2.60	1.80	2.00	1.60
GM113	2.25	1.80	2.25	2.30	1.80	1.60	1.80	2.00	3.00	2.00	3.00	2.60
GM114	1.27	1.60	2.00	1.30	0.80	1.20	1.40	1.20	2.00	2.00	2.60	1.40
GM115	2.50	1.80	2.30	2.13	2.40	1.80	2.20	1.60	2.60	1.80	2.40	3.00
GM116	1.30	1.70	1.37	1.80	1.20	1.00	0.60	1.60	1.40	2.40	2.40	2.00
GM117	1.40	1.20	1.80	1.30	1.20	1.20	1.80	1.20	1.60	1.20	1.80	1.40
GM118	2.20	2.30	1.80	1.40	1.80	2.00	1.20	1.40	2.60	2.60	3.00	1.40
GM119	1.20	0.90	1.50	0.90	1.00	0.60	1.20	0.60	1.40	1.20	1.80	1.20
GM120	2.60	2.07	1.50	1.30	2.20	1.40	1.40	1.20	3.00	2.80	1.60	1.40

* missing data due to technical failure

Overall mean values and standard deviations were calculated for each condition (Table 4.4)

TABLE 4.4: MEAN, MIN AND MAX VALUES OF VISUAL GAIN PERCEIVED AS NORMAL DURING EACH CONDITION (STDEV IN BRACKETS)

	Low visual clutter		High visual clutter	
	Condition A (Automatic)	**Condition B (Prompted)**	**Condition C (Automatic)**	**Condition D (Prompted)**
Mean	1.98 (0.49)	1.99 (0.45)	1.83 (0.34)	1.92 (0.49)
Min	1.59 (0.57)	1.57 (0.58)	1.41 (0.46)	1.52 (0.61)
Max	2.40 (0.56)	2.45 (0.50)	2.31 (0.5)	2.34 (0.58)

A repeated-measures 2-way ANOVA (environment x presentation method) demonstrated no significant effect for environment type ($F_{(3,17)}=0.85$ p=0.49) or for presentation method ($F_{(3,17)}=1.11$ p=0.37).

Since there was no difference between the presentation conditions, or the virtual environments, the data was collapsed for the subsequent analysis and testing (Table 4.5).

TABLE 4.5: MEAN, MIN AND MAX VALUES OF VISUAL GAIN PERCEIVED AS NORMAL ACROSS ALL CONDITIONS (STDEV IN BRACKETS)

	Data from all conditions collapsed for analysis
Mean	1.96 (0.26)
Min	1.55 (0.31)
Max	2.41 (0.33)

The mean perceived normal visual gain was compared with the real 'normal' visual gain (i.e. 1:1) using a one-sample t-test. The overall mean visual gain for the test population was 1.96:1. This was significantly different from the actual normal visual gain of 1:1, ($t_{(19)}=16.25$ p<0.001).

The minimum and maximum visual gains were compared using a paired-sample t-test. There was a significant difference between the minimum (1.55:1) and maximum (2.41:1) perceived normal visual gain ($t_{(19)}=10.29$, p<0.001).

The mean of the minimum visual gain perceived as normal was 1.55:1. This was also significantly different from the actual normal visual gain of 1:1 ($t_{(19)}=7.51$, p<0.001).

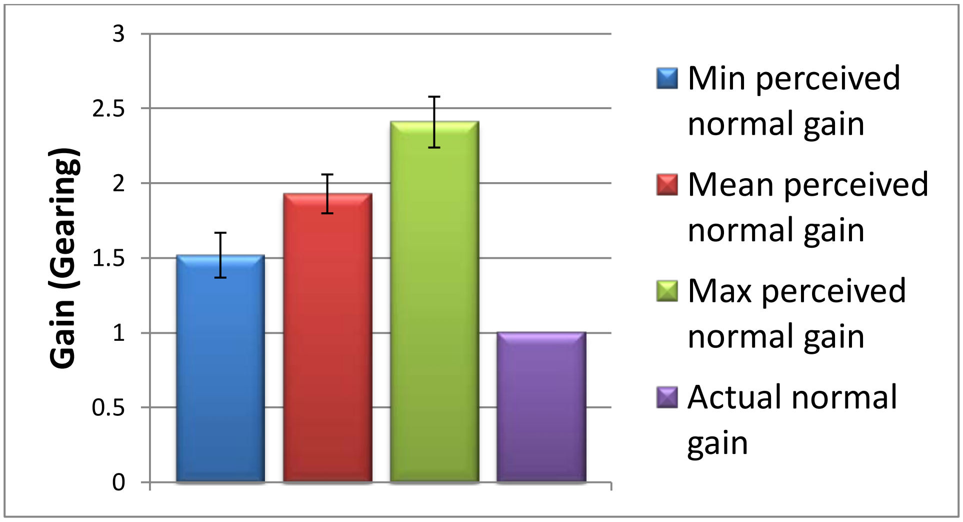

FIGURE 4.5: MEAN, MINIMUM AND MAXIMUM PERCEIVED NORMAL VISUAL GAIN COMPARED WITH ACTUAL NORMAL VISUAL GAIN

In summary, the results of this experiment support the hypothesis that the perceived normal visual gain is greater than 1:1 in this experimental setup. The results also support the hypothesis that the minimum and maximum perceived normal visual gain values are significantly different from each other (Figure 4.5). The results did not support the hypothesis that the perceived normal visual gain will be different between the prompted and automatic modes, nor the hypothesis that perception of normal visual gain will be more accurate in the visually cluttered scene.

4.4 DISCUSSION

This experiment supported previous findings that 1:1 ('normal') visual gain is perceived as too slow when walking on a self-paced treadmill, and also demonstrated that there is a significant range of visual gain which can be perceived as normal by an individual. Furthermore, upper and lower boundaries of the perceptual tolerance of normal visual gain were identified, both of which were above the ‘normal’ 1:1 ratio.

There are a number of factors affecting the perception of visual gain in treadmill-mediated VR. Firstly, treadmill walking itself gives the physical sensation of around a 10% increase in walk speed compared with actual speed (Distler, *et al*., 1998). This means that walking at 1m/s gives the feeling of walking at 1.1m/s.

Secondly, there is a distance compression phenomenon in VR which means that for each meter walked in VR, the participant’s visual perception would be that 0.74 meters had been travelled (Durgin, *et al*., 2005; Frenz, *et al*., 2007), effectively reducing the perceived optic flow speed.

Thus it is not surprising that the mean visual gain perceived as normal is significantly higher than 1:1. However, what is less clear is the real value of this normal visual gain, which has been reported to be as low as 1.3:1 (Durgin, *et al*., 2005) and as high as 2:1 (Kassler, *et al*., 2010).

In this experiment it was found that the mean perceived normal visual gain was 1.96:1 (i.e optic flow is 1.96 x walking speed). This was significantly different from the real normal visual gain of 1:1, and was also higher than the perceived visual gain found in some previous studies (e.g. Banton, *et al*., 2005; Durgin, *et al*., 2005). Kassler *et al*.’s study found a similar visual gain to that found in this experiment (Kassler, *et al*., 2010), although their virtual environment was a more open scene, which would produce a lower lamellar flow, which is believed to decrease the accuracy of perception of visual gain (Banton, *et al*., 2005).

There were a number of differences between this experimental design and those that have been carried out previously, and it may well be that this has contributed to the difference seen in the results. Previous studies have used preset speeds for the treadmill walking, with no control being given to the participant to select a preferred speed (Banton, *et al*., 2005; Durgin, *et al*., 2007; Durgin, *et al*., 2005; Durgin, Gigone, *et al*., 2005; Kassler, *et al*., 2010; Thurrell & Pelah, 2005). Even with the visual gain linked directly to the treadmill speed, this would result in unnaturally constant walk speed and optic flow. Whilst this fixed speed may allow a more consistent comparison to be made between trials, it is forcing a more artificial style of walking. The results of this experiment therefore are more applicable to current virtual rehabilitation approaches, which are moving towards the use of self-paced treadmills, and therefore using a more natural walking style (e.g. Fung, *et al*., 2004; Fung, *et al*., 2006). Furthermore, most of the previous studies used fixed handrails for support, and this additional tactile feedback may have contributed to the discrepancy in perceived visual gain. In contrast, the treadmill used in this experiment had sliding handrails which allowed normal free movement of the upper extremity during walking (Figure 4.3).

The main difference, however, is that the previous studies generally used variations on a design that identified a single perceptual boundary (Banton, *et al*., 2005; Durgin, *et al*., 2007; Durgin, *et al*., 2005; Durgin, K. Gigone, *et al*., 2005; Kassler, *et al*., 2010). This experiment found that there is in fact a range of visual gain that can be perceived as normal. Whilst the standard deviations in the results of previous studies are likely to identify the range within which visual gain differences cannot be perceived, they do not identify the range of normal visual gain 'tolerance'.

In this study it was found that, whilst participants were often aware of a change of visual gain, they classified the changes as within the tolerance of normal visual gain. The range of normal perceived visual gain was between 1.55:1 and 2.41:1, i.e. a change of +/- 20% around the mean. This is higher than the 15% sensitivity to visual gain changes found previously (Kearns, *et al*., 2002), which may be because the participants in this experiment were not asked to identify the point of noticeable change, but rather the point of departure from 'normal' visual gain. The fact that the visual gain values are higher supports the suggestion that there is a tolerance for a range of visual gain which is perceived as normal, beyond the range of 'no perceptible difference'.

The range of perceived normal visual gain found in this study was consistent regardless of whether the response was prompted every change or whether participants themselves noticed that the visual gain was no longer slow/normal/fast. In addition, there was no significant difference between the different environments.

It is clear from previous studies that there is considerable variation between individuals in the perception of visual gain (e.g. Kassler, *et al*., 2010), and this may make it difficult to identify a single optic flow multiplier that is optimum for all users. However, the results of this study suggest that it may not be necessary to identify a precise visual gain value to produce a realistic and believable experience for each individual. If the system is designed for a visual gain value at approximately the mean of the range of perceived normal, it is likely to fall within the tolerance range of most users, although further work is required to verify this.

This finding of a significant range of normal visual gain has implications for the design of treadmill-mediated Virtual Reality. On the positive side, it identifies that there is likely to be less need to have a precise visual gain value between the treadmill and optic flow to produce a realistic and believable user experience.

If the system is designed for a visual gain value at approximately the mean of the range of perceived normal, small changes in visual gain are unlikely to affect immersion. However, the minimum value identified as perceived normal is significantly above the normal visual gain of 1:1, and this does suggest that using slow optic flow (gain 0.5:1) to increase walking speed in VR may indeed involve a trade-off between therapeutic effect and realism, as a visual gain of 0.5:1 will fall well outside the acceptably normal visual gain perception range.

For applications where realism in the perception of optic flow is of prime importance, it will be necessary to identify other factors which may be able to influence walk speed without being associated with a reduction in ecological validity (chapter 5).

4.5 CONCLUSION

This is the first study to identify the range of visual gain values which lie within the tolerance of normal visual gain perception (1.55:1 – 2.41:1). Visual gain perception may be influenced by a variety of software, hardware and human factors, nevertheless these findings suggest that the tolerance of users to visual gain change may reduce the risk of visuo-motor dissonance in treadmill-mediated VR.

This study also identified a higher gain mismatch than previous studies, and this may be attributable to the more natural walking in the self-paced treadmill setup, as well as a change in methodological approach. Even the minimum perceived normal visual gain identified was significantly higher than the normal visual gain of 1:1, which has implications for realism when exploiting the benefits of lowered optic flow on walking speed.

Thus it remains necessary to identify further factors which may be able to facilitate an increase in walking speed without compromising visual realism. Section 2.2.2.2 identified audio as a component of VR with the potential to increase walking speed. If audio can be demonstrated to be effective within VR to increase walking speeds, then this could be a component which can be manipulated in applications where reducing the visual gain is not appropriate. Therefore, Chapter 5 investigates the use of audio cues as a factor to facilitate faster walking in VR.

5. INVESTIGATION OF THE EFFECT OF AUDIO CUE TEMPO ON WALKING IN TREADMILL-MEDIATED VIRTUAL REALITY

Walking speed may be manipulated by controlling the rate of optic flow in a treadmill-mediated virtual environment (chapter 3), but it is likely that reducing the visual gain will result in reduced realism in the perception of movement through the virtual environment (chapter 4).

However, it has been observed that audio tempo may also have an influence on walking speed (section 2.2.2.2.) although to date there is little research into the effect of audio on movement and perception of movement when interacting with virtual reality. If audio tempo can improve walking speeds, it is important to establish whether there is a similar influence in treadmill-mediated VR, in order to evaluate the potential of audio manipulation in virtual reality for rehabilitation, particularly in settings where lowering the visual gain is not appropriate.

5.1 INTRINSIC FREQUENCY AND CADENCE

Many physical systems have a natural frequency of oscillation, and studies would suggest that this is also true for the human body. Van Noorden & Moelants (1999) analysed a number of tapping and synchronisation studies and identified a natural movement frequency at around 1.8 to 2 Hz (2 taps per second). Interestingly, they also note that the historic classification of 'moderate' music speed (i.e. neither fast nor slow) is equivalent to a frequency of 1.5-2 HZ. However, it appears that this relates to normal healthy adults, and cannot necessarily be generalized to other populations.

Although van Noorden’s study concentrated on upper limb movement, it has been noted that during normal walking, individuals also demonstrate intrinsic walking patterns and rhythms, which remain remarkably constant over time (Durgin, *et al.*, 2007; Sekiya & Nagasaki, 1998). These consistent gait characteristics are predominantly related to cadence (step frequency) and walk ratio. Indeed, a study looking at preferred cadence over a 10 hour period found very similar natural frequencies, with a mean frequency of human locomotion of 2 steps per second (2Hz) (MacDougall & Moore, 2005). They also noted that this movement frequency is most efficient and is associated with optimal oxygen cost. This data was taken from normal healthy individuals in a natural setting, and it cannot be assumed that treadmill walking will necessarily be associated with the same natural frequency. Indeed, there is evidence that treadmill walking may be associated with a higher cadence than overground walking (e.g. Alton, *et al.*, 1998; Durgin, *et al.*, 2007; Stolze, *et al*., 1997), which may in part be due to the increased urgency to place the foot as the supporting limb is carried backwards (Alton, *et al*., 1998). However, these observations were made on motorized treadmills at preset fixed speeds and so were not under the control of the individual participant. Thus the cadence on self-propelled treadmills may not follow this pattern.

5.1.1 AUDIO CUEING TO FACILITATE WALKING

There is a strong link between auditory rhythms and motor activity, and the motor system is physiologically sensitive to arousal by the auditory system (Thaut, Kenyon, Schauer, & McIntosh, 1999). Indeed, studies in non-VR settings indicate that the use of **audio cues** can facilitate improved walk speed and quality (e.g. Ford, Wagenaar, & Newell, 2007; Lim, *et al*., 2005; Roerdink, *et al*., 2007; Suteerawattananon, *et al*., 2004).

A number of studies have found that **audio cueing** can improve walking in patients with Parkinson's Disease (PD). For example, a study of 24 PD patients found that auditory cueing improved cadence by 12%, resulting in a 16% increase in walking speed (Suteerawattananon, *et al*., 2004). However, a comprehensive review of the cueing literature highlighted a number of methodological flaws in many studies, although it nevertheless concluded that there was strong evidence to suggest that auditory cues can improve walking speed in PD (Lim, *et al*., 2005).

However, Parkinson's Disease is a disorder characterized by specific motor and sensory deficits, including a disruption to behaviours which depend upon precise timing (del Olmo, *et al*., 2006). Automatic sequencing of motor activity is generally controlled by an area of the brain known as the basal ganglia, which sends signals to the supplementary motor area to control timing and sequencing of motor actions such as walking or speech. Where there is disruption or damage to this area of the brain, the provision of rhythmic cues such as metronome beats can shift the dominance of the timing mechanism to the lateral premotor cortex (Alm, 2004), and in PD patients there is increased activation of this area of the brain (del Olmo, *et al*., 2006).

Thus whilst a number of studies have successfully demonstrated improved walking in PD using audio cueing (e.g. del Olmo, *et al*., 2006; McIntosh, Brown, Rice, & Thaut, 1997; Suteerawattananon, *et al*., 2004; Thaut *et al*., 1996), this facilitation may in part be due to the increased activation of the lateral premotor system in PD patients. It cannot therefore be assumed that similar facilitation would be observed in populations who do not have compromised gait-timing mechanisms. Nevertheless, more recent work has demonstrated that audio cueing may indeed facilitate improvements in walking in a variety of other populations, even without compromised gait timing mechanisms.

Ford, Wagenaar and Newell (2007) studied 11 stroke patients walking on a treadmill whilst synchronising arm and leg movements to a metronome beat. In this study, an audio frequency of 1.8Hz, which is close to the natural resonance frequency reported by van Noorden *et al.*(1999), was observed to improve gait quality and step length. A similar study of 10 stroke patients (Roerdink, *et al.*, 2007) found that there was an improvement in gait symmetry and cadence when participants were asked to synchronise heel-strike to regular auditory cues. However, both these studies used a fixed-speed treadmill, which limits the possible alterations to gait in response to the audio cueing.

It has previously been noted that the walk ratio remains invariant for most individuals, even over large changes in walking speed (e.g. Durgin, *et al.*, 2007; Sekiya & Nagasaki, 1998). Walking on a fixed-speed treadmill, any alteration in step length would have to be accompanied by a corresponding alteration in cadence (and vice versa), in order to maintain walking at the preset treadmill speed. This would result in an alteration in the walk ratio, and thus there may well be a tendency to resist changes in either step length or cadence when forced to walk at a constant preset speed. However, a comparison between fixed-speed and self-paced treadmill walking responses to audio cues would be necessary to establish this.

A very different study, of 20 healthy individuals walking on an athletics track, compared the effect of musical tempo and a metronome beat (Styns, *et al.*, 2007), and found that participants tended to walk faster with higher tempos. They noted that the effect was greater with music than with the metronome beat, but their sample was drawn predominantly from musicians, and therefore has an inherent confound which prevents generalisation of these results to a more heterogeneous population. Interestingly, they noted that the best synchronisation with the beat occurred at tempos equivalent to 1.75-2.2 Hz, again falling into the range of the natural resonance frequency.

A review of the use of music during exercise concluded that there is a predisposition to respond to the rhythmical elements of music (Karageorghis & Terry, 1997). The authors noted that synchronization of exercise to music resulted in increased work output and decreased perception of exertion, although this was only observed during submaximal physical activity. However, they did point out in this review that many of the early studies failed to control for elements of the musical selection such as genre, duration, preference, socio-cultural context, and activity type.

In almost all these studies (Ford, *et al*., 2007; Morris, 2005; Roerdink, *et al*., 2007; Styns, *et al*., 2007; Suteerawattananon, *et al*., 2004; Thaut, *et al*., 1996), participants were asked to explicitly synchronise to the beat, and so it is not clear how much of the improvement was due to a direct effect of rhythmic audio on gait timing, rather than a conscious attempt to move in a regular rhythm. Moreover, a review of studies investigating the effect of asynchronous (background) music on exercise concluded that the effect of such stimulus was unclear (Karageorghis & Terry, 1997), even though Styns *et al*. (2007) noted that participants who were unable to synchronise to the music still showed a significant effect on cadence, suggesting that background audio can still influence bodily activity.

These results suggest that the intrinsic tendency to synchronise to an external cue (Karageorghis, *et al*., 2009; Repp, 2005; van Noorden & Moelants, 1999) may be exploited for fitness or health benefits. Conversely, it can be suggested that indiscriminate use of background audio may have an unanticipated influence on movement, and thus this should be considered in the design of Virtual Reality for rehabilitation.

In summary, there is evidence that music can influence cadence and effort in exercise (Karageorghis & Terry, 1997), and also that audio beat tempo can alter walk speed (Lim, *et al*., 2005; Styns, *et al*., 2007; Suteerawattananon, *et al*., 2004) and decrease gait variability (del Olmo, *et al*., 2006; Roerdink, *et al*., 2007).

However, music can also influence mood during exercise (Karageorghis & Terry, 1997), and this altered mood can also modulate gait (Cluss, *et al*., 2006). Furthermore, the type of music also has a differential effect on gait (Ahmaniemi, 2007; Karageorghis, *et al*., 2009; Karageorghis & Terry, 1997). Nevertheless, it is clear from a wide range of studies that there is an underlying effect of audio tempo on gait, whether delivered as music or as a simple metronome-type beat.

These findings suggest that rhythmic audio could be incorporated in virtual reality applications for walking rehabilitation, and if correctly calibrated may serve to facilitate faster and more symmetrical walking. This could potentially add to the effect of optic flow manipulation, as well as being a useful tool for use when reducing optic flow is undesirable (section 4.4).

However, to date there is no research into the effect of audio cues in virtual reality, a situation confounded further as self-speed estimation is altered when walking in VR (Distler, *et al*., 1998; Durgin, Gigone, *et al*., 2005), and it is not known whether this visuo-motor modulation may also interact with any potential audio cues' effect on walking speed. Thus it cannot be assumed that the results of previous 'real-world' studies can be generalised for application in virtual reality for rehabilitation. Furthermore, although the overground audio cueing studies allow free walking, there is limited data relating to self-paced treadmill walking with audio cueing. Therefore an empirical study was conducted to determine whether audio cue tempo influences walk speed during self-paced treadmill walking with and without VR (section 2.3.1).

5.2 METHOD

This experiment investigates the influence of audio cue tempo on walk speed and cadence, as reported in previous real-world studies (Lim, *et al*., 2005; Styns, *et al*., 2007; Suteerawattananon, *et al*., 2004), when walking in VR using a self-paced treadmill.

The rate of optic flow in a virtual environment can affect walk speed, with increasing optic flow speed being associated with slower walking speeds (chapter 3). Furthermore, it has also been demonstrated that optic flow speeds at matched (1:1) visual gain are likely to be perceived as too slow (chapter 4). Thus raising the visual gain above 1:1 is likely to improve perceived realism but reduce walking speed. Therefore in this study, where perceptual realism is not a critical factor, a 1:1 visual gain was used, in order to minimise the potential confounding effect of optic flow on walking speed.

The amount of visual clutter can also have an influence on perception of optic flow (Durgin, *et al*., 2005), and therefore this experiment uses a virtual environment which is designed to provide high contrast peripheral visual cues without any central visual clutter or obstacles, and was back projected with stereo projection and a wide field of view, as detailed in section 3.3.2.

Audio cue tempo is an independent variable in this experiment. Previous studies have used a wide variety of audio cue tempos. This experiment used the same fast cue scaling as Suteerawattananon et. al. (2004), i.e. 25% above the baseline cadence (125% rate). In addition there was a condition with an audio cue 25% below the baseline cadence (75% rate) for comparison, and one matched to the baseline cadence.

There seems to be little consistency in the type of audio cue used for this type of experiment, therefore a footstep sound was selected, as this was felt to have more ecological validity than an abstract metronome beat.

5.2.1 DESIGN

Hypothesis 1: Audio cue tempo will have a significant effect on walk speed and cadence when walking on a self-paced treadmill without VR (c.f. Ford, *et al.*, 2007; Roerdink, *et al.*, 2007).

Hypothesis 2: Audio cue tempo will have a significant effect on walk speed and cadence when walking in treadmill-mediated VR.

Hypothesis 3: There will be a significant difference between the effects of audio cue tempo on treadmill walking with VR and without VR.

A repeated measures (within subjects) design was used (Table 5.1). Audio cue tempo and VR interaction were the independent variables, and walk speed and cadence the primary dependent variables.

TABLE 5.1: THE COMBINATION OF AUDIO AND VISUAL CUES FOR THE EXPERIMENTAL CONDITIONS. AUDIO RATE IS A PERCENTAGE OF BASELINE CADENCE

	No audio	**75% audio rate**	**100% audio rate**	**125% audio rate**
Treadmill + static image	condition 1	condition 2	condition 3	condition 4
Treadmill + VR	condition 5	condition 6	condition 7	condition 8

As discussed in section 5.1, walk ratio can remain remarkably consistent for an individual even with changes in speed or cadence. As it is hypothesised that both walk speed and cadence will vary between conditions, step length (speed/cadence) and walk ratio (step length/cadence) were secondary dependent variables derived from the primary variables.

Hypothesis 4: Audio cue tempo will have a significant effect on step length when walking on a self-paced treadmill.

Hypothesis 5: The within-subject walk ratio will remain constant with varying audio cue tempos (c.f. Durgin, *et al.*, 2007; Sekiya & Nagasaki, 1998).

5.2.2 MATERIALS AND APPARATUS

Previous studies have used fixed treadmill speeds, but this may place a constraint on the ability of the participant to alter cadence in response to changing audio tempo (section

5.1.1. Therefore, to allow for changes in cadence or step length without forcing a change in walk ratio, the treadmill used in this study was a self-paced motorised treadmill (as detailed in section 4.2.2).

The experiment used a low-clutter virtual environment similar to that described in chapter4, with a scene consisting of two parallel rows of vertical columns on either side of a walkway (Figure 5.1).

FIGURE 5.1: VIRTUAL WALKWAY USED IN THE STUDY

The scene was rendered into an interactive format using Open Scene Graph, and the virtual camera was set to match the starting position of the participant, with a horizontal fov of 100^o and a height of 1.6m above the ground plane. The interactive stereoscopic scene was projected onto the screen using a pair of Christie 7700 Lumen projectors with polarising filters. To minimise visual distraction, the room was darkened for the experiment, with the main light source being the display screen itself.

The speed of the treadmill belt was monitored using an optical sensor and used as input to update the virtual camera view in real-time. This speed was updated every frame (30fps) at a resolution of 0.01 m/s (Appendix A)

The audio component was the sound of a footstep on a hard surface, loaded as a .wav file into the Open Scene Graph application. The sample sound was 0.4 seconds long, sampled at 705 kbps. It was delivered to the participant via Logitech ClearChat™ wireless stereo headphones, in order to mask the sound of the treadmill belt and the participants' own footsteps.

Cadence was recorded during a baseline test (two experimenters independently counted the number of steps per 30 seconds block, and a mean of these 6 values was then converted to number of steps/second). The mean walk speed was calculated from the total distance walked during the 3 minutes (as recorded from the treadmill controller to the computer). The participants' baseline cadence was entered into the software application, and this was used as a reference to calculate the audio tempo for each condition using a bespoke C++ algorithm (Appendix C).

5.2.3 PARTICIPANTS

Participants were thirteen healthy volunteers (9 female, 4 male) between the ages of 21 and 54 (mean age 34.6) (Table 5.2).

TABLE 5.2: DEMOGRAPHIC DETAILS OF PARTICIPANTS FOR GAIN MATCH STUDY

ID	Age	Gender
AV101	54	F
AV103	39	M
AV104	23	F
AV105	35	F
AV106	31	F
AV107	42	M
AV108	39	F
AV109	35	M
AV110	28	M
AV111	43	F
AV112	37	F
AV114	21	F
AV115	23	F

Ethical approval was obtained from the University of Portsmouth School of Creative Technologies ethics committee. Participants were drawn from the University of Portsmouth staff and students.

5.2.4 PROCEDURE

Prior to the task all participants gave their informed consent and were given the experimental instructions (Appendix F).

The participants spent a few minutes familiarising themselves with the equipment and walking on the treadmill. Trials were not initiated until the participant was able to maintain a steady comfortable walking pace on the adapted treadmill.

The audio beat was played to the participants before the start of the experimental phase, and they were instructed to adjust the volume of the headphones to a strong but comfortable level. This volume was maintained throughout the experimental session.

Due to the larger number of experimental conditions (8 conditions) compared to the study in chapter 3 (4 conditions) it was felt that five minutes for each trial may led to fatigue, potentially confounding the results. Therefore, a duration of 3 minutes was set for each trial.

A 3 minute baseline walk was recorded with no audio input, and the visual scene on screen remained static (condition 1, Table 5.1). Participants were instructed to walk at a self-selected pace for the duration of each 3 minute trial. No instructions were given regarding whether or not they should attempt to synchronise with the beat. If they explicitly asked if they should synchronise, the experimenter simply reiterated that this was entirely up to the participant.

Participants walked in each of the remaining experimental conditions in randomised order. For each trial, treadmill walking was initiated in the absence of interactive VR and audio. When the participant was walking steadily the next trial was initiated. Each lasted for 3 minutes. Audio was either absent (VR only) or played at a pre-set tempo calculated from the baseline cadence. The interactive walkway was either static (audio only) or dynamically linked to the treadmill belt with a 1:1 visual gain (VR conditions).

During each trial the belt speed was recorded around 30 times per second, and the mean walk speed (m/s) was calculated from this data. The number of steps taken every 30 seconds was recorded as before, and the mean cadence for each trial was calculated from this.

5.3 RESULTS

A mean value for the cadence was calculated for each experimental condition (Table 5.3). Audio rate is calculated as a percentage of baseline cadence.

TABLE 5.3: MEAN CADENCE (STEPS/S) FOR EACH INDIVIDUAL IN EACH CONDITION

ID	**Cadence in non-VR conditions**				**Cadence in VR conditions**			
	0	**75%**	**100%**	**125%**	**0**	**75%**	**100%**	**125%**
AV101	1.75	1.41	1.73	2.02	1.75	1.32	1.72	2.13
AV103	1.88	1.80	1.86	1.87	1.84	1.84	1.83	1.79
AV104	1.48	1.53	1.49	1.79	1.53	1.19	1.48	1.79
AV105	1.87	1.83	1.79	1.77	1.80	1.77	1.84	1.79
AV106	1.81	2.05	1.89	1.96	1.93	2.01	1.69	1.90
AV107	1.45	1.47	1.42	1.47	1.47	1.49	1.42	1.49
AV108	1.83	1.82	1.83	2.09	1.81	1.66	1.89	2.04
AV109	1.85	1.89	1.83	1.83	1.62	1.70	1.66	1.72
AV110	1.75	1.73	1.73	1.69	1.65	1.73	1.65	1.69
AV111	1.90	2.00	1.98	2.19	2.04	2.01	2.02	1.92
AV112	1.79	2.10	1.93	1.88	2.00	1.89	2.03	2.19
AV114	1.41	1.28	1.40	1.43	1.36	1.55	1.78	1.69
AV115	1.77	1.39	1.74	1.85	1.69	1.73	1.72	1.91

A mean value for the walking speed was calculated for each experimental condition (Table 5.4). Audio rate is calculated as a percentage of baseline cadence.

TABLE 5.4: OVERALL MEAN WALK SPEED (M/S) FOR EACH CONDITION

ID	**Audio rate in non-VR conditions**				**Audio rate in VR conditions**			
	0	**75%**	**100%**	**125%**	**0**	**75%**	**100%**	**125%**
AV101	1.14	0.97	1.08	1.46	1.17	0.87	1.16	1.50
AV103	1.08	1.26	1.17	1.36	1.23	0.98	1.22	1.31
AV104	0.92	0.99	1.00	1.21	0.97	0.69	0.96	1.17
AV105	1.23	1.28	1.27	1.29	1.28	1.25	1.32	1.28
AV106	1.18	1.43	1.31	1.36	1.36	1.33	0.94	1.24
AV107	0.83	0.85	0.85	0.89	0.83	0.87	0.78	0.85
AV108	1.13	1.30	1.27	1.61	1.29	1.14	1.49	1.60
AV109	1.36	1.44	1.42	1.32	1.04	1.09	1.00	1.07
AV110	1.30	1.27	1.30	1.21	1.11	1.30	1.12	1.25
AV111	1.14	1.16	1.15	1.36	1.22	1.15	1.18	1.13
AV112	1.00	1.65	1.38	1.30	1.30	1.12	1.30	1.45
AV114	0.85	0.72	0.79	0.87	0.75	0.95	1.09	1.05
AV115	1.11	0.83	1.18	1.36	1.16	1.20	1.19	1.39

A repeated measures 2-way MANOVA (VR x audio cue tempo) demonstrated a significant effect of audio tempo on walk speed ($F_{(3,36)}=6.96$, $p<0.01$). *Post hoc* analysis revealed that the fast audio cue condition was significantly higher than the baseline condition ($p<0.01$), and higher than the slow audio condition ($p<0.05$) and the matched audio condition

($p<0.01$), but there was no significant difference in walk speed between any of the other conditions.

There was also a significant effect of audio tempo on cadence ($F_{(3,36)}=4.36$ $p<0.01$). *Post hoc* analysis revealed that the cadence in the fast audio cue condition was significantly higher than the baseline condition ($p<0.01$), and the slow audio condition ($p=0.05$) and the matched audio condition ($p<0.05$), but there was no significant difference in cadence between any of the other audio conditions.

There was no effect for VR on walk speed ($F_{(1,12)}=0.75$ $p=0.4$) or cadence ($F_{(1,12)}=0.004$ $p=0.95$), nor any interaction between VR and audio cues ($F_{(6,72)}=1.64$ $p=0.15$).

Both speed and cadence were significantly higher in the fast audio cue condition than the other conditions, and this was not influenced by the presence or absence of VR (Table 5.5).

TABLE 5.5: MEAN AND STANDARD DEVIATION FOR WALK SPEED (M/S) AND CADENCE (STEPS/S)(STDEV IN BRACKETS)

	No audio		**75% audio rate**		**100% audio rate**		**125% audio rate**	
	Walk speed	*Cadence*	*Walk speed*	*Cadence*	*Walk speed*	*Cadence*	*Walk speed*	*Cadence*
Treadmill + static image	1.09 (0.16)	1.73 (0.17)	1.16 (0.28)	1.71 (0.27)	1.17 (0.19)	1.74 (0.19)	1.28 (0.20)	1.83 (0.22)
Treadmill + VR	1.13 (0.18)	1.73 (0.20)	1.07 (0.19	1.68 (0.25)	1.13 (0.19)	1.75 (0.18)	1.25 (0.20)	1.85 (0.19)

A repeated measures 2-way MANOVA (VR x audio cue tempo) demonstrated a significant effect of audio tempo on step length ($F_{(3,36)}=6.91$ $p<0.01$). *Post hoc* analysis revealed that step length in the fast audio cue condition was significantly higher than the baseline condition ($p<0.01$), and the slow audio condition ($p<0.05$) and the matched audio condition ($p<0.01$), but there was no significant difference between any of the other audio conditions.

There was no significant effect for audio tempo on walk ratio ($F_{(3,36)}=1.45$ $p=0.24$).

There was no effect for VR on step length ($F_{(1,12)}=1.45$ $p=0.25$) or walk ratio ($F_{(1,12)}=1.54$ $p=0.24$), and no interaction between VR and audio cues ($F_{(6,72)}=1.68$ $p=0.14$).

Step length was significantly greater in the fast audio condition than the other conditions, but walk ratio remained unaffected. This was not influenced by the presence or absence of VR (Table 5.6).

TABLE 5.6: MEAN STEP LENGTH (M) AND WALK RATIO (M/STEPS/S)(STDEV IN BRACKETS)

	No audio		**75% audio rate**		**100% audio rate**		**125% audio rate**	
	Step length	*Walk ratio*	*Step length*	*Walk ratio*	*Step length*	*Walk ratio*	*Step length*	*Walk ratio*
Treadmill + static image	0.63 (0.06)	0.37 (0.04)	0.67 (0.07)	0.40 (0.05)	0.67 (0.07)	0.39 (0.04)	0.69 (0.05)	0.38 (0.04)
Treadmill + VR	0.65 (0.05)	0.38 (0.04)	0.64 (0.06)	0.38 (0.07)	0.65 (0.07)	0.37 (0.04)	0.68 (0.06)	0.37 (0.04)

The walk speed increase seen in the fast audio condition was produced by a combination of increased cadence and increase step length, whilst maintaining the walk ratio (Figure 5.2).

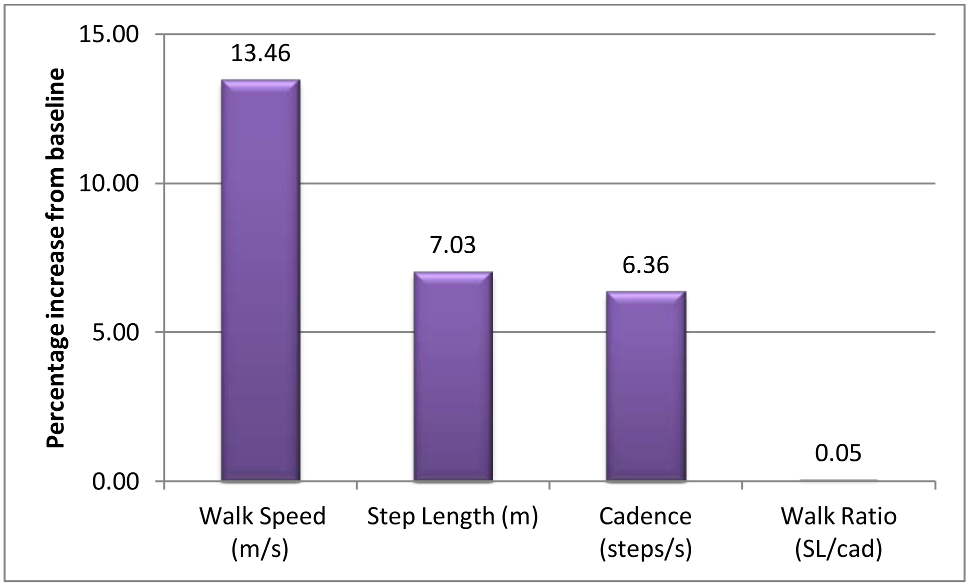

FIGURE 5.2: THE PERCENTAGE INCREASE FROM BASELINE TO FAST AUDIO CONDITION FOR EACH OF THE DEPENDENT VARIABLES

In summary, the results of this experiment support the hypotheses that audio cue tempo will have a significant effect on walk speed and cadence when walking on a self-paced treadmill, and when walking in VR. The results did not support the hypothesis that there will be a significant difference between the effects of audio cue tempo on treadmill walking with VR and without VR.

The results also supported the hypotheses that audio cue tempo will have a significant effect on step length when walking on a self-paced treadmill, and that the within-subjects walk ratio will remain constant with varying audio cue tempos.

5.4 DISCUSSION

A significant effect for audio cue frequency on treadmill walk speed was found (Table 5.2), with a significant increase in walk speed associated with audio cues above baseline cadence, but no effect on walk speed for audio cues below baseline cadence (Figure 5.2). This is consistent with the findings of previous studies (Lim, *et al*., 2005; Styns, *et al*., 2007; Suteerawattananon, *et al*., 2004) and also demonstrates that the effect of audio cueing in overground walking and fixed-speed treadmill walking also holds for self-paced treadmill walking.

Although there is a natural tendency for humans to synchronise movements to external audio rhythms (Cluss, *et al*., 2006; del Olmo, *et al*., 2006; Karageorghis, *et al*., 2009; Roerdink, *et al*., 2007; Suteerawattananon, *et al*., 2004), this is not necessarily achieved solely by increasing cadence, but by a combination of changes to step length and cadence. As audio cue tempo increases there is an associated increase in cadence, and if walk ratio is maintained this will be accompanied by an increase in step length and thus a faster walk speed. During overground walking, this allows walk ratio to be maintained, but on fixed speed treadmills a change in cadence will force a change in walk ratio (section 5.1.1).

However, since walk ratio is already lower during treadmill walking than overground walking (Alton, *et al*., 1998; Stolze, *et al*., 1997), increasing cadence at a fixed speed will reduce the stride length, and hence walk ratio, even further from normal. However, in this experiment using a self-paced treadmill, the increases in cadence were accompanied by increases in step length, allowing walk ratio to be maintained and walk speed increased (Figure 5.2). This supports the observations of Durgin *et al*. (2007), who noted that step length/cadence (walk ratio) is maintained at a relatively constant ratio across varying walking speeds. This is an important finding, as treadmill gait training aims to focus on both walk speed and gait quality (section 1.1.1), and thus a mechanism which can improve gait speed without disrupting normal walk ratio could be a useful tool in rehabilitation.

The mean audio cue tempo used for the fast audio condition was around the natural resonant frequency of 2Hz, and in this audio condition there was indeed a significant increase in cadence, supporting previous observations that there is a tendency to synchronise with external rhythms, particularly at resonant frequency (Cluss, *et al*., 2006; del

Olmo, *et al*., 2006; Karageorghis, *et al*., 2009; Roerdink, *et al*., 2007; Suteerawattananon, *et al*., 2004). However, the other audio conditions had no significant effect on either cadence or walk speed, and this experiment only used one 'fast' audio condition, and so it is not possible to conclude whether similar gait changes would be seen with different multiples of the baseline cadence, nor whether the natural frequency of 2Hz is an upper limit for audio-cued cadence changes. Further work is required to address these issues.

The addition of optic flow in the VR condition did not significantly alter the effect of the audio cues on gait. Although it has been previously noted that speed perception is altered in VR (section 4.1), it has also been reported that a connection exists between auditory cortex and spinal motor neurons (Repp, 2005), and therefore it is possible that visual input will not interfere with the rhythmic synchronisation with the audio cues. However, it is also known that perturbed optic flow which conflicts with the walking speed can significantly alter gait (section 2.2.3) and it cannot be assumed that the findings of this experiment would be the same in conditions where optic flow and audio cues were incongruent.

Furthermore, this investigation was carried out on a population of normal healthy adults. Thus although there were significant walk-speed increases in the presence of fast audio cues (section 5.3) it cannot yet be concluded that the addition of fast audio cues to treadmill-mediated VR will necessarily increase walk speed in other populations, particularly those whose gait is compromised by injury, illness or pain.

It should also be noted that the mean walking speed in the baseline conditions in this experiment was 1.09 m/s (StDev 0.16). This is considerably lower than the average overground walking speed (section 3.5) of 1.5 m/s (Knoblauch, *et al*., 1996), although again it is similar to the steady treadmill walking speeds previously found with self-paced treadmills (Varraine, *et al*., 2002). Since this type of treadmill is often used in treadmill-VR interfaces (Apfelbaum, *et al*., 2007; Fung, *et al*., 2006; Lichtenstein, *et al*., 2007), it is important to identify any differences in walking compared with fixed-paced treadmills or overground walking (Chapter 6).

5.5 CONCLUSION

This is the first experiment to demonstrate that the frequency of audio cues can significantly influence walk speed during self-paced treadmill walking, with and without VR. This supports and extends previous studies, which have indicated that higher rate rhythmic audio cues may give rise to an increased walk speed during overground walking.

Importantly, this is also the first study to report that the increased walk speed associated with higher audio cue frequency did not disrupt the normal walk ratio.

The results suggests that the inclusion of faster rate audio cues may be of benefit in improving walk speed in virtual reality, and therefore may be particularly useful in applications where reduction of visual gain is unacceptable. However, this study did not look at the interaction between varying optic flow rates and audio cuing, and this would require further study to establish whether the facilitating effects of the audio and visual input could be combined (chapter 7). Further work is also required to investigate this phenomenon in clinical populations (chapter 7), and to identify the optimal audio cue tempo for facilitating faster walking.

Nevertheless, the indiscriminate addition of music or sound effects to virtual environments may confound rehabilitation or exercise goals, and the potential effect of such audio content should be considered during the design of VR walking applications.

6. INVESTIGATION OF THE DIFFERENCES IN GAIT BETWEEN OVERGROUND AND SELF-PACED TREADMILL WALKING

The benefits of treadmill training for rehabilitation are well established (Section 1.1.1), and there is also increasing evidence of the potential of VR to facilitate motor rehabilitation (Section 1.2). However, whilst intrinsic factors in VR such as optic flow (Chapter 3) or audio cues (Chapter 5) may have the potential to improve walking speeds, there is also evidence that the use of a treadmill may itself contribute to reduced walking speeds (chapter 3). Since treadmills are increasingly becoming the interface of choice for walking in virtual environments, further investigation is needed to understand the ways in which normal walking may be influenced by the use of a treadmill interface.

6.1 TEMPORAL AND SPATIAL GAIT PARAMETERS

6.1.1 NORMAL WALKING

Locomotor slowing is of particular concern in rehabilitation (section 1.1), with one of the primary goals of treadmill-based rehabilitation being to establish an increase in walking speeds (section 1.1.1).

The speed of walking is determined by a combination of spatial (step-length) and temporal (cadence) components. The step length is the distance between the two feet when walking, measured from heel strike (first point of contact of one foot) to heel strike of the other foot. Cadence is the frequency of individual steps from heel-strike on one foot to heel-strike on the other foot. Walking speed is the product of step-length and cadence. Although it is possible for an almost infinite combinations of step-length and cadence to produce a given walking speed, it has been noted that walk ratio (the relationship between step-length and cadence) is remarkably consistent across a wide range of walking speeds (Sekiya & Nagasaki, 1998).

Thus for treadmill walking to be considered to be comparable to overground walking for the purposes of rehabilitation, the walking speeds and walk ratio should be similar. However, treadmills do not necessarily provide the same biomechanical experience as overground walking, and indeed even the type of treadmill used may differentially influence these gait parameters.

6.1.2 TREADMILL WALKING

When walking overground, the supporting foot is placed on the ground and the centre of gravity moves forwards as the free leg swings through to the next heel strike. In contrast, when treadmill walking the supporting leg moves backwards with the treadmill belt, which may give rise to an increased sense of urgency to place the foot of the swing limb (Alton, *et al*., 1998). This is consistent with the observation that cadence tends to be higher during treadmill walking compared with overground walking at similar speeds (Alton, *et al*., 1998; Lee & Hidler, 2008; Stolze, *et al*., 1997). Although at fixed treadmill speeds this increased cadence would be associated with a shorter stride length and no change in walking speed, it is interesting to note that it has been observed that a fixed speed is perceived as faster on a treadmill compared with the same speed when overground walking (Alton, *et al*., 1998).

If treadmill speeds are perceived as fast compared with overground walking, then it might be anticipated that, given the ability to self-select a walking speed, self-paced treadmill walking speeds are likely to be lower than free-walking overground, and indeed studies using self-paced treadmills seem to report average walking speeds of around 1.1 m/s (chpater 3, Varraine, *et al*., 2002), considerably lower than the average overground walking speed of 1.5 m/s (Knoblauch, *et al*., 1996). However, there are no studies making a direct comparison between overground walking and self-paced treadmill walking, and so it is not known whether the lower speeds seen in the studies are attributable to the treadmill, or to another factor. Further work is required to investigate this (section 6.2).

Furthermore, since fixed-speed treadmill walking is associated with higher cadence and shorter stride length, this will result in a lower walk ratio. As walk ratio is relatively constant during normal walking, this does suggest that treadmill walking causes some disruption to the spatio-temporal control of gait. It may be possible that the lower walking speeds seen in self-paced treadmill walking may also be associated with lowered walk ratio, but it is also possible that the self-paced treadmill may allow more natural walking and be associated with a more normal walk ratio. Further work is needed to establish this (section 6.2).

6.1.3 ABNORMAL WALK PATTERNS ASSOCIATED WITH ILLNESS OR DISABILITY

Walk ratio is known to be disrupted in some clinical populations, with relatively short stride length to cadence seen in, for example, multiple sclerosis (Rota, Perucca, Simone, & Tesio, 2011), Parkinson’s Disease (Murray, Sepic, Gardner, & Downs, 1978), old age (JudgeRoy, Davis, & Õunpuu, 1996; Menz, Lord, & Fitzpatrick, 2003), and chronic pain (Keefe & Hill, 1985; Lamoth, Stins, Pont, Kerckhoff, & Beek, 2008). However, it is not known how this altered gait may vary with self-paced treadmill walking. Further work is required to investigate this (section 6.2).

In summary, it is clear that overground walking and self-paced treadmill walking cannot be assumed to be comparable with respect to cadence, walk speed, step length and walk ratio. Furthermore, there is likely to be a difference between healthy and clinical populations. Therefore an empirical study was conducted to determine whether there is a difference in walking overground compared with self-paced treadmill walking (section 1.2.3).

6.2 METHOD

This study investigates whether the low walking speeds measured previously in self-paced treadmill walking (section 6.1.2) are lower than overground walking speeds when compared within-subjects. It also investigates the differential effect of overground and self-paced treadmill walking on cadence, step length and walk ratio, and compares the results of a population of adults without pain to a population with chronic pain.

Some of the clinical conditions identified in section 6.1.3 are complex, and may have several factors which influence gait parameters. For example, multiple sclerosis and Parkinson's disease are both characterised by significant neurological deficits. Whilst it remains important to understand walking patterns in these populations, this experiment focuses on patients with chronic pain, without concomitant morbidity which affects walking, in order to minimise confounding factors.

6.2.1 DESIGN

Hypothesis 1: Walk speed will be significantly slower when walking on a self-paced treadmill compared with overground walking, in both non-pain and pain populations

Hypothesis 2: Cadence will be significantly lower when walking on a self-paced treadmill compared with overground walking, in both non-pain and pain populations

Walk ratio has been observed to differ between treadmill and overground walking (section 6.1.2) due to changes in step length. As it is hypothesised that both walk speed and cadence will be lower for treadmill walking, step length (speed/cadence) and walk ratio (step length/cadence) were secondary dependent variables derived from the primary variables.

Hypothesis 3: Step length will be significantly shorter when walking on a self-paced treadmill compared with overground walking, in both non-pain and pain populations

Hypothesis 4: Walk ratio will be significantly lower when walking on a self-paced treadmill compared with overground walking, in both non-pain and pain populations

A repeated-measures mixed design was used (Table 6.1). The walking modality and the presence of pain were the independent variables. Walk speed and cadence were the primary dependent variables, and step length and walk ratio were secondary dependant variables.

TABLE 6.1: THE EXPERIMENTAL CONDITIONS FOR THE PAIN AND NON-PAIN GROUPS

	Non-Pain	**Pain**
Overground	Condition 1	Condition 2
Treadmill	Condition 3	Condition 4

The **pain intensity** and **pain affect** were also recorded at the start of the experiment.

6.2.2 MATERIALS AND APPARATUS

The overground walk was carried out using a survey wheel in a long (around 50m) hospital corridor.

Previous studies comparing treadmill and overground walking have used fixed treadmill speeds, but this may place a constraint on the ability of the participant to alter cadence or step length (section 6.1.2). Therefore, to allow for changes in cadence or stride length without forcing a change in walk ratio, the treadmill used in this study was a self-paced motorised treadmill (section 4.2.2). The treadmill responded dynamically to the speed of the user in real time. The belt speed was recorded to a computer using an optical sensor at a resolution of 0.01m/s.

FIGURE 6.1: THE STATIC IMAGE OF THE WALKWAY USED IN THE TREADMILL WALKING CONDITION

The treadmill was placed 1.5m in front of a 2.44m wide x 3.05m high screen. A static image of a 3-dimensional model of a virtual walkway was created using SoftImage XSI software. The scene consisted of two parallel rows of vertical columns on either side of a walkway (Figure 6.1). Due to constraints in the experimental facility, the scene was projected monoscopically.

6.2.3 PARTICIPANTS

A total of 36 volunteers participated in the experiment. Patients with musculoskeletal pain on walking were recruited from the Jewish Rehabilitation Hospital (Laval, Quebec) and the Constance Lethbridge Rehabilitation Centre (Montreal, Quebec). Healthy volunteers were recruited from the staff and student body of the Jewish Rehabilitation Hospital (Laval, Quebec), the Constance Lethbridge Rehabilitation Centre (Montreal, Quebec) and McGill University (Montreal, Quebec)(Table6.2). Immediately following this experiment, these 36 participants also took part in the experiment in Chapter 7.

TABLE 6.2: DEMOGRAPHIC DETAILS OF PARTICIPANTS IN TREADMILL AND PAIN / AUDIO STUDIES

ID	Age	Gender	Initial pain intensity	Initial pain affect
301	80	M	5	1
302	64	F	0	0
303	54	M	7	7
304	24	F	1	0
305	69	F	4	5
306	46	F	4	3
307	53	M	2	0
308	52	F	0	0
309	62	M	0	0
310	64	F	7	4
311	60	M	6	8
312	46	M	1	1
313	48	F	7	5
314	53	M	6	8
315	53	M	6	3
316	67	F	2.5	0.5
317	54	M	5.5	0
318	54	M	2	2
319	39	M	0	0
401	43	F	n/a	n/a
402	49	M	n/a	n/a
403	68	M	n/a	n/a
404	22	M	n/a	n/a
405	55	M	n/a	n/a
406	59	M	n/a	n/a
408	51	F	n/a	n/a
409	63	F	n/a	n/a
410	24	F	n/a	n/a
411	59	F	n/a	n/a
412	25	M	n/a	n/a
413	26	F	n/a	n/a
414	59	F	n/a	n/a
415	66	M	n/a	n/a
416	41	F	n/a	n/a
417	40	M	n/a	n/a
418	48	M	n/a	n/a

The participants were assigned to one of two groups based on the presence (n=19) or absence (n=17) of musculoskeletal pain in the upper or lower limb that compromised walking (Table 6.3). All were able to walk independently and had no other medical condition which limited walking (e.g. stroke, Parkinson's disease, heart disease etc).

TABLE 6.3: SUMMARY OF PARTICIPANT DEMOGRAPHICS FOR THE PAIN AND NON-PAIN GROUPS

	Age	**Gender**	**Pain intensity**	**Pain affect**
Non pain (N=17)	22 - 68 mean 46.9	8 female 9 male	N/A	N/A
Pain (N=19)	24 - 80 mean 55.8	8 female 11 male	mean 3.5	mean 2.5
Pain intensity and pain affect are scored on a 1-10 ***numeric rating scale*** *(NRS) on the day of testing.*				

Ethical approval was obtained from the Comité d'éthique de la recherche des établissements du CRIR (Montreal, Canada). All participants were able to converse fluently in either English or French, and gave their informed consent prior to inclusion in the experiment (Appendix G).

6.2.4 PROCEDURE

Baseline pain intensity and pain affect scores were recorded using a 1-10 **numeric rating scale** (NRS)(McCaffrey & Beebe, 1993).

For each of the conditions, the participants were asked to walk at their preferred speed, with no instruction or feedback given during the walking trials.

The 6-minute walk test (6MWT - Enright, 2003) is a standardised gait assessment often used in clinical or rehabilitation settings, and therefore this study used the 6MWT for the overground walking condition. After participants had given informed consent and been briefed on the experiment, a 6MWT was administered using a survey wheel in a long hospital corridor (approx 50m). During this walk test, the numbers of steps taken across marked 10m sections were recorded. The step length and walk ratio were derived from the overground walk speed and cadence.

After a rest period of around 20 minutes, the participants were familiarized with the self-paced treadmill, and when they were able to maintain a steady speed and cadence on the treadmill, they completed a three minute treadmill walk test. There is no standardised protocol similar to the 6MWT for assessing gait using a treadmill. It had been observed (chapter 5) that 3 minutes of self-paced treadmill walking is sufficient to establish a steady walk speed, therefore a 3 minute test was used for the treadmill baseline speed.

Cadence was recorded during the treadmill trials (two experimenters independently counted the number of steps every 30 seconds, and these values were averaged and then converted to steps/second).

6.3 RESULTS

A mean value was calculated for the walk speed (m/s) and cadence (steps/s) for the treadmill and overground walking conditions (Table 6.4).

TABLE 6.4: INDIVIDUAL MEAN WALK SPEED AND CADENCE FOR EACH EXPERIMENTAL CONDITION

ID	Walk speed (m/s)		Cadence (steps/s)	
	Overground	Treadmill	Overground	Treadmill
301	1.36	0.70	2.31	1.50
302	0.84	0.29	1.50	1.50
303	1.32	0.79	1.62	1.42
304	1.44	1.21	2.05	1.93
305	1.10	1.12	1.79	1.70
306	1.34	0.82	1.94	1.37
307	1.27	0.60	1.81	1.60
308	1.21	0.99	1.76	1.63
309	1.07	0.70	2.08	1.97
310	1.02	0.70	1.51	1.51
311	0.98	0.60	1.83	1.48
312	1.33	1.24	2.04	1.90
313	0.90	0.68	1.70	.88
314	0.71	0.70	1.43	1.18
315	0.92	0.63	1.49	.93
316	0.92	1.16	1.70	1.91
317	1.08	0.83	1.65	1.72
318	1.47	1.44	1.91	1.80
319	1.75	1.60	1.94	1.93
401	1.47	1.28	2.03	1.93
402	1.33	1.26	1.87	2.00
403	1.37	1.53	1.88	1.90
404	1.74	1.55	2.06	1.88
405	1.35	0.81	1.87	1.61
406	1.65	1.01	1.86	1.57
408	1.33	0.79	1.82	1.43
409	1.59	1.00	2.11	1.90
410	1.17	0.83	1.87	1.76
411	1.90	1.60	2.33	2.30
412	1.36	1.18	1.84	1.67
413	1.43	1.14	2.00	1.73
414	1.44	0.71	2.01	1.41

415	1.33	0.80	1.91	1.76
416	1.25	0.67	1.87	1.47
417	1.53	1.10	1.89	1.79
418	1.37	1.14	1.78	1.79

A repeated measures MANOVA (walk modality x pain group) conducted on the walk speed and cadence for all participants showed a significant difference between pain and non-pain groups for speed ($F_{(1,34)}=8.68$, $p<0.01$) and cadence ($F_{(1,34)}=5.78$ $p<0.05$), as well as a significant difference between overground and treadmill conditions for both speed ($F_{(1,34)}=64.28$ $p<0.01$) and cadence ($F_{(1,34)}=25.53$ $p<0.01$). However, there was no significant interaction effect ($F_{(1,34)}=1.28$ $p=0.27$) between pain and walk condition for speed and no significant interaction ($F_{(1,34)}=0.22$ $p=0.64$) between pain and walk condition for cadence.

Speed and cadence were significantly lower for treadmill walking in both groups compared with overground walking, and the pain group had significantly lower walking speeds and cadence than the non-pain group for both walk modalities (Table 6.5 and Figure 6.2)

TABLE 6.5: OVERALL MEAN WALK SPEED (M/S) AND CADENCE (STEPS/S) FOR GROUP (PAIN OR NON-PAIN) AND WALK MODALITY (OVERGROUND OR TREADMILL)(STDEV IN BRACKETS)

		No Pain (n=17)	**Pain (n=19)**
Overground	*Walk speed*	1.45 (0.18)	1.16 (0.26)
	Cadence	1.94 (0.14)	1.79 (0.23)
Treadmill	*Walk speed*	1.08 (0.29)	0.88 (0.33)
	Cadence	1.76 (0.23)	1.57 (0.32)

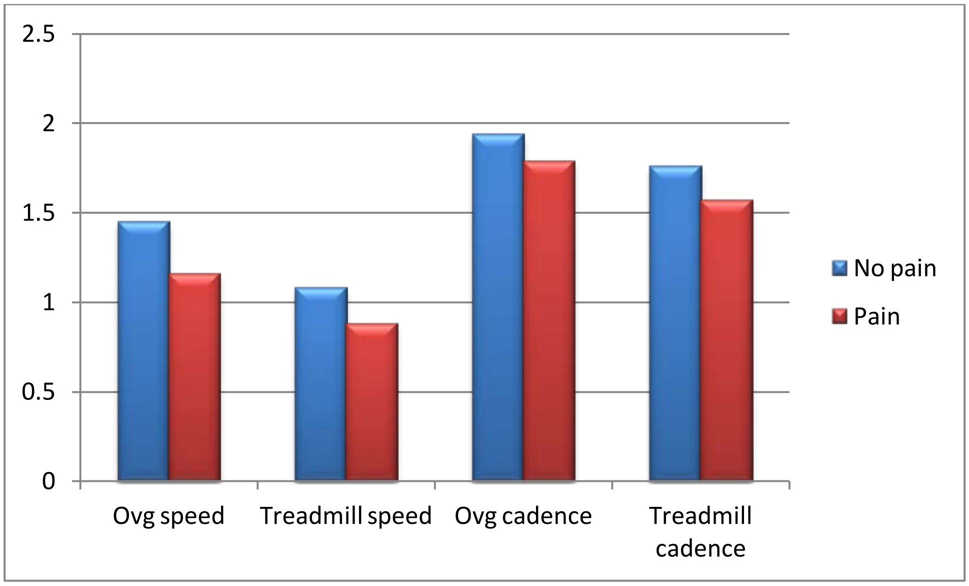

FIGURE 6.2: WALK SPEED (M/S) AND CADENCE (STEPS/S) FOR EACH OF THE CONDITIONS

A repeated measures MANOVA (walk modality x pain group) conducted on the step length and walk ratio for all participants showed a significant difference between pain and control groups for step length ($F_{(1,34)}$=4.61 p<0.05) but no significant difference between pain and control groups for walk ratio ($F_{(1,34)}$=0.09 p=0.77).

There was also a significant effect of walk modality on step length ($F_{(1,34)}$=25.7 p<0.001), but no significant effect of walk modality on walk ratio ($F_{(1,34)}$=0.18 p=0.67).

Step length was significantly lower for treadmill walking compared with overground walking in both experimental groups, and step length was significantly lower in the pain group compared with the non-pain group for both walking conditions (Table 6.6). There was no significant difference in walk ratio within or between groups (Figure 6.3).

TABLE 6.6: MEAN STEP LENGTH (M) AND WALK RATIO (M/(STEPS/S)) FOR GROUP (PAIN OR NON-PAIN) AND WALK MODALITY (OVERGROUND OR TREADMILL)(STDEV IN BRACKETS)

		No Pain (n=17)	**Pain (n=19)**
Overground	*Step length*	0.74 (0.06)	0.64 (0.11)
	Walk ratio	0.38 (0.04)	0.36 (0.07)
Treadmill	*Step length*	0.61 (0.11)	0.56 (0.16)
	Walk ratio	0.35 (0.06)	0.38 (0.18)

FIGURE 6.3: STEP LENGTHH (M) AND WALK RATIO FOR EACH OF THE CONDITIONS

In summary, the results support the hypotheses that walk speed, cadence and step length will be lower when walking on a self-paced treadmill compared with overground walking in both pain and non-pain groups. The results do not support the hypothesis that walk ratio will be lower on a self-paced treadmill. The results also show that all dependent variables were lower for the pain group than the non-pain group.

6.4 DISCUSSION

A number of studies have compared overground and treadmill walking, but they have generally set the treadmill speed to match the preferred overground speed and compared gait biomechanics between the two conditions (e.g. Alton, *et al.*, 1998; Lee & Hidler, 2008). Whilst useful in establishing that treadmill walking is biomechanically comparable to overground walking for therapeutic purposes, these studies fail to fully investigate changes in temporal characteristics between the two walking modes, which can only become apparent if the participants are allowed to select their own pace on the treadmill as well as on the overground component.

The treadmill walking speeds seen in this study are comparable to those seen in previous research (Varraine, *et al.*, 2002), and also in the studies in chapters 3 and 5. The findings of this experiment confirm that a self-selected walking speed on a treadmill (approx 1.1m/s) will be significantly lower than the self-selected overground walking speed (approx 1.5m/s).

It is known that walking speeds are perceived as faster on a treadmill (Alton, *et al.*, 1998), and it may be that contributes to the decrease in speed seen in treadmill walking.

However, the misperception of treadmill walking speed is only around 10% (Durgin, *et al.*, 2007), and this study observed a difference in walk speed of around 25%, and thus this cannot account fully for the differences in walk speed seen between the two environments.

Previously, fixed-speed treadmill gait studies have noted an increased cadence compared with overground walking (section 6.1.2). This is characteristic of cautious gait in a variety of settings (e.g slippery conditions, fear of falling) during which the step length is reduced for a given walking speed (Zijlstra, de Bruin, Bruins, & Zijlstra, 2008), giving rise to a lower walk ratio. It might be postulated that this type of cautious gait could account for the decrease in walk speed seen in the treadmill condition.

However, with a self-paced treadmill there is less urgency to place the foot, which should reduce the tendency to increase cadence. Indeed, this study did demonstrate a lower cadence for treadmill walking than for overground walking, and this was associated with an overall decrease in walking speed. However, the step-length in this experiment was reduced proportionately to the cadence, resulting in a more normal walk ratio, in contrast to observations with fixed-speed treadmills, where there was a significant difference in walk ratio (e.g. Alton, *et al.*, 1998; Stolze, *et al.*, 1997). Thus the results do not support the hypothesis that the slower walking may be attributable to cautious gait patterns.

The consistency in walk ratio between the self-paced treadmill and overground walking seen in this study indicate that the self-paced treadmill supports a more normal walking pattern than fixed-speed treadmills. However, there remains the problem that walking is slower on the self-paced treadmill than overground walking, and further work is needed to establish the reasons for this difference.

It is clear from the findings of this study that the ability to maintain a normal walk ratio on a self-paced treadmill is not confined to healthy adults, but is also true for patients with chronic pain. Although the pain group had lower mean scores across all dependent variables, the direction of effect of the two walking modalities was the same as for the non-pain group, i.e a reduction of all variables except walk ratio when treadmill walking. It is interesting to note that even in this group with compromised walking they are able to maintain the same walk ratio when walking on the self-paced treadmill compared with overground walking, suggesting that this may be a suitable tool to interface with VR for this clinical group, although it still must be borne in mind that the baseline walk speed will be slower on the treadmill than overground.

Thus it seems that, whilst treadmills offer a convenient interface to VR, and an effectively infinite walking surface in a small controlled space, there is a trade-off between convenience, walking speed and natural gait. Overground walking provides the most natural walking experience, but requires a large amount of space to cover any significant distance. It also requires the use of a head-mounted display to interface with VR, and this in itself will constrain the walking area, in addition to the potential for visual distortion (Riecke *et al.,* 2005). A fixed-speed treadmill can be easily interfaced to VR, and can be set to a speed that matches the preferred overground speed. However, it is associated with an alteration to normal walking patterns (section 6.1.2) and it is not known what implications this may have for rehabilitation. Self-paced treadmills are also easily interfaced to VR and allow walking which is closer to natural overground walking. However, the preferred speed is lower than overground walking, which is not ideal when a common goal of locomotor rehabilitation is to increase the baseline walking speed (section 1.1).

If treadmills and VR are to be a useful tool for rehabilitation then a solution which combines natural walking with higher speeds is required. Chapters 3 and 5 identified components of VR which can facilitate increased walking speeds on self-paced treadmills. It was also noted (section 5.3) that walk ratio was not changed during the increased walking speeds associated with higher audio tempos. Thus it may be possible to combine the natural walking of the self-paced treadmill with the facilitation offered by manipulation of audio and visual cues to obtain the desired rehabilitation outcomes.

However, the consistent walk ratios seen in the audio cue study (chapter 5) was in a population of healthy young adults, and it cannot be assumed that the same result would be seen in elderly or clinical populations, Further work is required to establish this (chapter 7).

A limitation of this study is that, due to experimental constraints, the walking conditions were not presented in counterbalanced order, but instead all participants started with the overground walk. Thus it is possible that an order effect was introduced, and that treadmill walking speeds were lower due to fatigue. However, all participants were well rested between conditions, in order to minimise this confound. Furthermore, all the participants took part in a subsequent study (chapter 7) following the one detailed in this chapter, and were able to maintain faster walking speeds subsequent to the initial treadmill walk, and so it seems unlikely that the decreased walking speed found in this study was due to an order effect. However, it may have had some influence on the magnitude of the effect, and a further study using counterbalancing of the conditions would be necessary to confirm these initial findings.

A further limitation is that the standardised overground protocol requires 6 minutes walking. However, the experimental design limited the treadmill walk to only 3 minutes. It would be anticipated that average walk speed would be slower across the longer time period, but in fact the reverse was seen, and so this is unlikely to be a significant confound. However, in follow-up studies it would be preferable for the walk tests to be for comparable durations.

6.5 CONCLUSIONS

This is the first study to demonstrate that self-paced treadmills have the potential to support a natural relationship between step length and cadence in both healthy populations and those with chronic pain. However, used without any other intervention they are likely to result in walking speeds somewhat lower than the preferred overground speed, and so need to be combined with other components of VR in order to facilitate faster walking whilst allowing natural gait. These are important findings, as treadmill gait training aims to focus on both walk speed and gait quality (section 1.1.1), and whilst self-paced treadmills are clearly well-suited to supporting natural walk ratios, they are associated with lower baseline walking speeds.

Previous studies have demonstrated that walking speed may be increased in healthy adults by slowing the optic flow (chapter 3) or by the addition of fast tempo audio cues (chapter 5), but further work is necessary to establish whether these effects are also seen in the patients with chronic pain (chapter 7).

7. INVESTIGATION OF THE EFFECT OF AUDIO AND VISUAL CUE TEMPO ON WALK SPEED IN PATIENTS WITH CHRONIC MUSCULOSKELETAL PAIN

One of the primary goals of treadmill-based rehabilitation is to establish an increase in walking speed (section 1.1.1). There is also evidence that treadmill-mediated VR may be of use in supporting this therapeutic goal (sections1.2, 4.4, 5.4). However, it has also been demonstrated that the use of a treadmill interface may result in lower baseline walking speeds than overground walking, both in a healthy population and also in a population with musculoskeletal pain (chapter 6).

Thus to take advantage of the benefits of VR in engagement (section 1.2.1), reduction of perceived pain (section 1.2.2) and improved movement (section 1.2.3), as well as the safe, controllable and space-saving rehabilitation environment that treadmill-mediated VR can offer, may mean that patients have a lower baseline walking speed when interacting with VR.

However, there is also evidence that adjusting the optic flow (chapter 3) or adding audio cues (chapter 4) may be of benefit in facilitating higher walking speeds, but these studies were carried out on healthy adults and it is not known how the results might be applied to clinical populations. Further investigation is needed to understand how particular clinical populations may respond to these facilitating cues in VR whilst walking on a self-paced treadmill.

Although the intrinsic movement frequency seems to be similar across a wide range of the normal population, illness and disability is often associated with psychomotor slowing, and even though a movement frequency of around 2Hz is most efficient and is associated with optimal oxygen cost (MacDougall & Moore, 2005), frequencies of 1.5Hz or even lower are commonly seen in conditions of ill-health (e.g. del Olmo, *et al*., 2006; Roerdink, *et al*., 2007; Silver, Macko, Forrester, Goldberg, & Smith, 2000; Suteerawattananon, *et al*., 2004). Indeed, it is evident in Chapter 6 that the baseline (overground) cadence for the healthy population was close to the natural resonant frequency (2Hz), but for the pain group cadence was only 1.8Hz, dropping to 1.6 Hz on treadmill walking. As walk ratio is maintained, these lower cadence frequencies are associated with slower walking speeds, and this slower movement gives rise to reduced activity and increasing disability, and is inefficient in terms of energy required (Simmonds, *et al*., 2006).

Slow walking has been identified as a correlate of many clinical conditions (sections 1.1 and 6.1.3) such as stroke (e.g. L Ada, *et al.*, 2009), Parkinson's Disease (e.g. Pohl, *et al.*, 2003), intermittent claudication (Gardner & Poehlman, 1995), chronic musculoskeletal pain (Ferrell, Josephson, Pollan, Loy, & Ferrell, 1997), multiple sclerosis (Rota, *et al.*, 2011), and old age (JudgeRoy, *et al.*, 1996). Some of these conditions are complex and may be associated with multiple co-morbidities (e.g. stroke, intermittent claudication) or neurological deficits (e.g. stroke, Parkinson's Disease, multiple sclerosis) and are outside the scope of the investigations in this thesis. Therefore this experiment focuses on patients with chronic musculo-skeletal pain, without concomitant morbidity which affects walking, in order to minimise potential confounding factors.

7.1 VIRTUAL REALITY AND CHRONIC MUSCULOSKELETAL PAIN

Locomotor slowing is often a correlate of musculoskeletal pain across a variety of conditions (section 1.1), and the frequent failure to resume usual movement speed can lead to chronic reduction in activity and increasing disability (Hart, *et al.*, 2000). It appears that individuals with pain can move faster when challenged to but tend not to if unchallenged, perhaps due to the anticipation of pain with faster movement (Simmonds, *et al.*, 2006) and thus a therapeutic approach which can facilitate faster movements, without the deleterious effects of the anticipation of pain, may be able to offer improvements in walk speed for patients with musculoskeletal pain.

The potential benefits of VR for rehabilitation (Section 1.2) include increased engagement with therapy (e.g. Bryanton, *et al.*, 2006; Rizzo & Kim, 2005; Thornton, *et al.*, 2005) and distraction from pain (e.g. Hoffman *et al.*, 2004; Hoffman, *et al.*, 2003; Hoffman, *et al.*, 2000; Hoffman, *et al.*, 2001), and thus would appear to offer significant potential for locomotor rehabilitation for conditions associated with musculoskeletal pain.

To date, the most extensive work in VR and pain has been carried out by Hoffman *et al.* (e.g. Hoffman *et al.*, 2004; Hoffman, *et al.*, 2003; Hoffman, *et al.*, 2001; Hoffman, *et al.*, 2000), and although many of the studies are of small size or single case studies, they offer some insight into the potential of VR to reduce the perception of pain.

One of the earliest controlled trials comparing VR with a non-VR condition was carried out on 12 burn patients during range of motion treatment sessions (Hoffman, Patterson *et al.*, 2000). All patients reported significant reductions in pain during VR exposure compared with the non-VR condition. However, this study did not compare VR with other traditional distractor techniques, so was unable to conclude if the VR offered additional pain relief compared with lower-cost distracters, such as video games.

However, a small case study carried out in the same year, on 2 adolescent burns victims, compared the distracting effects of VR and Nintendo64 (Hoffman, Doctor, Patterson, Carrougher, & Furness, 2000). The patients reported a much greater reduction in pain with the immersive VR than with the video game, although such case study results should be interpreted with caution due to the low numbers of participants and the difficulty in controlling experimental conditions.

Building on Hoffman's early work, a study of 59 paediatric cancer patients compared the perceived pain during a painful medical procedure, with distraction provided by either a video game delivered via a headset or the same game delivered through a computer screen, or a non-distraction control condition (Gershon, *et al*., 2003). Although the researchers found a significant reduction of pain and distress in the headset condition compared with the control, both video game conditions showed a similar trend of reduction of pain and distress. Although the authors refer to the headset condition as 'VR' and the same game without a headset as 'non-VR', in fact the differences in the conditions are only in the visual delivery mode. Whilst this may have influenced the level of immersion in the game, the study did not compare interactive VR with a true non-VR condition. Nevertheless, the results do support Hoffman *et al*.'s findings that VR can be an effective adjunct to therapy to reduce perceived pain.

Whilst the work to date has yielded promising results, there is little understanding as to the neural mechanisms involved in this modulation of pain perception. It is possible that VR and other distracters may demand significant attentional resources, reducing those available for processing pain, and this has been the focus of some more recent studies in pain and VR.

A small study of 8 male participants investigated the effect of immersive VR on pain-related brain activity (Hoffman *et al*., 2004). Participants underwent a 7 min fMRI (functional Magnetic Resonance Imaging) scan whilst being presented with thermal pain stimuli, with and without immersion in VR. There was a significant reduction in brain activity in areas associated with both affective (mood) and sensory (experience) components of pain. This study found convergence between the subjective and objective evidence that VR reduces perception of pain, and although it did only look at experimentally induced pain, it seems plausible that a similar reduction in brain activation occurs during VR analgesia for clinical (non-experimental) pain.

Whilst reducing the effects of acute and chronic pain is the focus of much research and attention, pain itself is a necessary and important phenomenon, alerting the body to both potential and actual harm, and our knowledge of the normal pain mechanisms may help us to understand and exploit the ability of VR to attenuate pain perception. There has been much interest over the past few decades around the potential to use distracting signals to divert attention away from painful or noxious stimuli. The pain-gate theory (Melzack & Wall, 1965) has been refined and extended, and it is now understood that there is a complex pain-modulating control system descending from the mid-brain area (Mayer, Wolfle, Akil, Carder, & Liebeskind, 1971). A study of the neurobiology of VR pain attenuation (Gold, Belmont, & Thomas, 2007) noted that this mid-brain area receives inputs from cortical regions involved in attention and emotion, and it may be that the attention involved in immersive VR activates this inhibitory mechanism, decreasing pain perception via the descending pain-modulation pathways.

Further work is required to investigate the specific components of VR and their contribution to pain modulation, including the relative contributions of immersive distraction, active interaction and emotional engagement. Nevertheless, there is evidence that VR can contribute significantly to reduced pain perception, and this effect may be able to be usefully exploited in VR-modulated locomotor rehabilitation.

Moreover, if the analgesic properties of VR can be combined with an environment which improves movement speed, patients may be able to engage in rehabilitation at a higher functional level, leading to increased long-term gains in mobility.

It was demonstrated that audio cues can improve walk speed in healthy adults (chapter 5), and this is achieved by an increase in both cadence (movement frequency) and step length (section 6.3). There is also data to suggest that audio cues can improve walk speed and cadence in Parkinson's Disease (e.g. del Olmo, *et al*., 2006; Lim, *et al*., 2005; McIntosh, *et al*., 1997; Suteerawattananon, *et al*., 2004; Thaut, *et al*., 1996) and also in stroke patients (Ford, *et al*., 2007; Roerdink, *et al*., 2007). However, both Parkinsons' Disease and stroke are associated with neurological deficits resulting in motor dysfunction, and it cannot be assumed that similar facilitation would be observed in populations with chronic pain, where slow movement has a less direct neurological aetiology.

Furthermore, reduced rates of optic flow are also associated with faster walking speeds (chapter 3). It could also be possible that the slowing of optic flow rate, and the reduction in perceived self-motion, may reduce the fear of pain associated with increased walking speeds. However, chronic pain demands a high level of attention, which may distract attention from other tasks (Eccleston & Crombez, 1999; Hart, *et al*., 2000), and therefore it may be the case that patients with chronic pain would be less able to attend to the visual and auditory cues that would otherwise lead to faster walking speeds.

Thus, whilst it is not known how patients with pain will respond to audio and visual cues, it is clear that this is an area which warrants further investigation. If either the optic flow or auditory cue speed has an influence on patients walking with pain then it may be of benefit in VR rehabilitation. Furthermore, it is not known whether visual and audio cue effects will be additive or even opposing. Therefore an empirical study was conducted to determine what effect varying the rate of audio and optic flow cues has on walking on people with and without musculoskeletal pain (section 2.3.1).

7.2 METHOD

This experiment investigates whether the previously observed influence of optic flow rate (chapter 3) and audio cue tempo (chapter 5) on walk speed would be present in patients with musculoskeletal pain, and also to investigate the effect of combining audio and visual cues in treadmill-mediated VR.

Previous work (chapter 3) identified that an optic flow speed of 0.5 x baseline walk speed was associated with a significant increase in walk speed, and so this was selected as a level for this experiment. To provide a comparison and control, two other visual conditions were also included, optic flow matched to baseline walk speed and absent optic flow (static image). The experiment used a virtual environment which was designed to provide high contrast peripheral visual cues without any central visual clutter or obstacles (section 2.3.2).

7.2.1 DESIGN

Hypothesis 1: Optic flow rate below baseline walk speed will be associated with a significant increase in the speed of walking on a self-paced treadmill in patients with musculoskeletal pain (c.f. chapter 3).

Hypothesis 2: Audio cue tempo above baseline cadence will be associated with a significant increase in the speed of walking on a self-paced treadmill in patients with musculoskeletal pain (c.f chapter 5).

Hypothesis 3: The effect of audio and optic flow cues on walking will be significantly different between the patients with musculoskeletal pain and the non-pain group.

Hypothesis 4: There will be a significant decrease in perceived pain in patients with musculoskeletal pain when walking in treadmill-mediated VR (c.f Hoffman *et al*., 2004).

The audio cue rates were scaled from the baseline cadence using the same scaling as in section 5.2.1 (75%, 100% and 125% of baseline cadence).

The experimental design was a mixed 3 x 4 x 2 factorial experiment with two within-subjects factors (optic flow x audio) (Table 7.1), and one between subjects factor (pain).

TABLE 7.1: THE COMBINATION OF AUDIO AND VISUAL CUES FOR THE EXPERIMENTAL CONDITIONS FOR THE TWO GROUPS

	No audio	**audio rate 75% baseline cadence**	**audio rate 100% baseline cadence**	**audio rate 125% baseline cadence**
No optic flow	condition 1	condition 4	condition 7	condition 10
optic flow 50% baseline speed	condition 2	condition 5	condition 8	condition 11
optic flow 100% baseline speed	condition 3	condition 6	condition 9	condition 12

Audio cue tempo, optic flow rate and presence of pain were the independent variables. Walk speed was the dependent variable.

In addition, the pre-and post- experiment pain intensity and pain affect were recorded as dependent variables for the musculoskeletal pain group.

7.2.2 MATERIALS AND APPARATUS

The treadmill used in this study was a self-paced motorised treadmill (section 4.2.2). The treadmill responded dynamically to the speed of the user in real time. The belt speed was recorded to a computer using an optical sensor at a resolution of 0.01m/s.

The treadmill was placed 1.5m in front of a 2.44m wide x 3.05m high screen. A 3-dimensional model of a virtual walkway was created using SoftImage XSI software. The scene consisted of two parallel rows of vertical columns on either side of a walkway (Figure 6.1).

The virtual camera was set to match the starting position of the participant, with a horizontal field of view of 80^{o} and a height of 1.6m above the ground plane. The scene was back-projected onto the screen using a single (monoscopic) projector. To minimise visual distraction, the room was darkened for the experiment, with the main light source being the display screen itself.

The CAREN software (Computer Assisted Rehabilitation Environments, Motek BV) was used to control the hardware system and synchronize the instantaneous treadmill speed and scene progression via a software gearing module. The audio component was also synchronised by the CAREN software. The audio was the sound of a footstep on a hard surface, loaded as a .wav file into the open scene graph application. The sample sound was 0.4 seconds long, sampled at 705 kbps. It was delivered to the participant via Logitech ClearChat™ wireless stereo headphones.

7.2.3 PARTICIPANTS

A total of 36 volunteers participated in the experiment. Patients with musculoskeletal pain on walking were recruited from the Jewish Rehabilitation Hospital (Laval, Quebec) and the Constance Lethbridge Rehabilitation Centre (Montreal, Quebec). Healthy volunteers were recruited from the staff and student body of the Jewish Rehabilitation Hospital (Laval, Quebec), the Constance Lethbridge Rehabilitation Centre (Montreal, Quebec) and McGill University (Montreal, Quebec). Immediately prior to this experiment he participants took part in the experiment in chapter 6. Demographic details of the participants can be found in Table 6.2.

The participants were assigned to one of two groups based on the presence (n=19) or absence (n=17) of musculoskeletal pain in the upper or lower limb that compromised walking (Table 6.3). All were able to walk independently and had no other medical condition which limited walking (e.g. stroke, Parkinson’s disease, heart disease etc).

Ethical approval was obtained from the Comité d'éthique de la recherche des établissements du CRIR (Montreal, Canada). All participants were able to converse fluently in either English or French, and gave their informed consent prior to inclusion in the experiment (Appendix G).

7.2.4 PROCEDURE

Prior to this experiment, all participants took part in the experiment detailed in chapter 6, therefore, to minimise unnecessary repetition of data, the treadmill walk speed and cadence data from the study was used for condition 1 (baseline) in this experiment.

The participants walked in each of the remaining experimental conditions in randomised order. For the visual cues, the baseline walk speed was scaled (by a factor of 0, 0.5 or 1) and the optic flow through the virtual environment was set at this speed for the duration of the trial. For the audio cues, the baseline cadence was scaled (by a factor of 0, 0.75, 1 or 1.25), and the footstep beat was played at this tempo for the duration of the trial.

During pilot testing, it was found that 2 minutes of walking was sufficient to obtain consistent walk speed data, and therefore each of the trials was limited to 2 minutes duration.

For each of the trials, the participants were asked to walk at their preferred speed on the treadmill. For each trial, treadmill walking was initiated in the absence of optic flow or audio. When participants reached 75% of their baseline walk speed, the next trial was initiated automatically. The participants then continued to walk on the treadmill for 2 minutes, whilst being presented with combinations of audio and visual cues. The participants were able to rest between trials as required, and completed a total of twelve 2-minute trials.

Participants were instructed to walk at a self-selected pace for the duration of each 2 minute trial. No instructions were given regarding whether or not they should attempt to synchronise with the beat. If they explicitly asked if they should synchronise, the experimenter simply reiterated that this was entirely up to the participant.

Participants from the pain group were asked to give a verbal Numeric Rating Scale (NRS) rating of perceived pain intensity and pain affect immediately after completing the experiment.

7.3 RESULTS

The walk-speed of the participants was automatically recorded to the treadmill control computer during each trial, and the mean walk speed (m/s) was calculated from this data (Table 7.2).

TABLE 7.2: INDIVUDUAL MEAN WALK SPEEDS FOR EACH EXPERIMENTAL CONDITION

ID	**No optic flow**				**Optic flow 50% baseline**				**Optic flow 100% baseline**			
Audio	**None**	**75%**	**100%**	**125%**	**None**	**75%**	**100%**	**125%**	**None**	**75%**	**100%**	**125%**
301	.70	1.20	.70	1.14	1.10	1.23	1.13	1.18	.52	1.07	.88	.51
302	.29	1.06	.47	.49	.96	.48	.69	.89	1.05	.82	.36	1.00
303	.79	.67	.66	.70	.75	.89	.94	.70	1.04	.95	1.01	.90
304	1.21	1.57	1.55	1.50	1.49	1.52	1.49	1.58	1.57	1.51	1.45	1.58
305	1.12	1.24	1.33	1.44	1.25	1.24	1.25	1.15	1.08	1.27	1.04	1.33
306	.82	1.08	1.07	1.22	.96	1.04	1.05	1.17	1.03	1.09	1.08	1.07
307	.60	.46	.43	.68	.40	.48	.47	.54	.38	.37	.36	.51
308	.99	1.52	1.53	1.54	1.51	1.40	1.43	1.45	1.46	1.37	1.43	1.32
309	.70	.78	1.17	.76	.86	1.20	1.04	.88	1.06	1.10	1.11	1.15
310	.70	.81	1.03	.67	.75	.76	.62	.86	.78	.93	.99	.79
311	.60	1.33	1.31	1.35	1.18	.58	1.17	1.14	.84	1.11	.94	1.10
312	1.24	1.53	1.56	1.57	1.45	1.47	1.32	1.16	1.49	1.37	1.46	1.53
313	.68	.79	.71	.95	.76	.83	.78	.96	1.07	.81	.80	.86
314	.70	.74	.68	.88	.57	.49	.59	.73	.50	.78	.68	.73
315	.63	.89	.73	.58	.72	.90	.72	.63	.68	.83	.64	.78
316	1.16	1.24	1.33	1.34	1.33	1.36	1.26	1.28	1.38	1.21	1.20	1.25
317	.83	.96	.95	1.13	1.02	.86	1.16	1.06	.97	1.00	1.15	1.00
318	1.44	1.58	1.56	1.74	1.51	1.42	1.47	1.51	1.50	1.41	1.46	1.63
319	1.60	1.55	1.66	1.66	1.58	1.61	1.63	1.77	1.73	1.51	1.58	1.65
401	1.28	1.42	1.45	1.39	1.23	1.27	1.24	1.30	1.23	1.27	1.36	1.22
402	1.26	1.52	1.35	1.55	1.30	1.09	1.12	1.23	1.27	1.31	1.05	1.35
403	1.53	1.77	1.63	1.73	1.52	1.60	1.50	1.56	1.55	1.53	1.55	1.50
404	1.55	2.04	2.07	1.75	2.00	1.96	2.05	2.09	1.74	2.03	2.05	2.02
405	.81	1.53	.91	1.41	1.49	1.46	1.47	1.52	1.43	1.31	.87	1.17
406	1.01	1.36	1.32	1.34	1.28	1.28	1.30	1.33	1.17	.78	1.08	1.25
408	.79	1.41	1.37	1.28	1.37	.86	1.25	1.40	1.35	1.34	1.05	1.18
409	1.00	1.12	1.00	.97	1.12	1.07	1.10	1.18	1.25	1.11	.90	1.16
410	.83	1.25	1.26	1.30	1.30	1.28	1.22	1.22	1.24	1.29	1.26	1.33
411	1.60	1.81	1.92	1.82	1.54	1.94	1.89	1.81	1.48	1.55	1.71	1.49
412	1.18	1.42	1.43	1.42	*	*	*	*	*	*	*	*
413	1.14	1.35	1.32	1.45	1.32	1.39	1.26	1.43	1.37	1.27	1.18	1.43
414	.71	1.48	.98	1.57	1.30	1.58	1.54	1.68	1.62	1.40		1.56
415	.80	1.43	1.53	.98	1.50	1.54	1.45	1.53	1.52	1.34	1.52	1.45
416	.67	.85	.89	.88	.89	.89	.82	.89	.66	.82	.80	.68
417	1.10	1.78	1.72	1.71	1.63	1.70	1.29	1.69	1.74	1.74	1.78	1.68
418	1.14	1.40	1.24	1.29	1.44	1.23	1.28	1.46	1.37	1.25	1.33	1.37

* missing data due to technical failure

The pre- and post-test pain scores were recorded for each individual, and mean and StDev values calculated (Table 7.3)

TABLE 7.3: PRE- AND POST-TEST NRS PAIN SCORES FOR EACH OF THE PARTICIPANTS IN THE PAIN GROUP

ID	Initial pain intensity	Initial pain affect	Post-test pain intensity	Post-test pain affect
301	5.0	1.0	5.0	5.0
302	*	*	*	*
303	7.0	7.0	7.0	7.0
304	1.0	.0	3.0	3.0
305	4.0	5.0	6.0	6.5
306	4.0	3.0	4.0	4.0
307	2.0	.0	2.5	2.0
308	.0	.0	.0	.0
309	.0	.0	.0	.0
310	7.0	4.0	7.0	4.0
311	6.0	8.0	5.0	6.0
312	1.0	1.0	2.0	1.0
313	7.0	5.0	4.5	4.0
314	6.0	8.0	6.0	8.0
315	6.0	3.0	7.0	5.0
316	2.5	.5	2.5	1.0
317	5.5	.0	3.0	.0
318	2.0	2.0	4.0	4.0
319	0	0	0	0
Mean	3.59	2.74	3.74	3.26
StDev	2.62	2.89	2.36	2.62

7.3.1 THE EFFECT OF AUDIO AND VISUAL CUES ON WALK SPEED

A repeated measures ANOVA (optic flow x audio cue tempo x pain) demonstrated a significant effect of audio tempo on walk speed ($F_{(3,99)}=10.41$ $p<0.001$), but no significant effect of optic flow on walk speed ($F_{(2,66)}=2.01$ $p=0.14$).

Post hoc analysis revealed that the walk speed in the fast audio condition was significantly faster than the no-audio condition (p<0.001) and faster than the 100% audio condition (p<0.05), but was not significantly different from the slow audio condition (p=0.3). The walk speed in the slow audio condition was also significantly faster than in the no-audio condition (p<0.001), and approaching significance between the slow audio condition and the matched audio condition (p=0.07). There was no significant difference between any other pairs of audio conditions (Table 7.4).

TABLE 7.4: OVERALL MEAN WALK SPEEDS (M/S) IN EACH OF THE EXPERIMENTAL CONDITIONS (STDEV IN BRACKETS)

	No audio		**audio rate 75% baseline cadence**		**audio rate 100% baseline cadence**		**audio rate 125% baseline cadence**	
	Pain	*No pain*	*Pain*	*No pain*	*Pain*	*No pain*	*Pain*	*No pain*
No optic flow	0.88 (0.33)	1.08 (0.30)	1.10 (0.35)	1.47 (0.28)	1.07 (0.41)	1.37 (0.35)	1.12 (0.40)	1.40 (0.29)
optic flow 50% baseline speed	1.06 (0.36)	1.39 (0.24)	1.04 (0.38)	1.38 (0.33)	1.06 (0.34)	1.36 (0.30)	1.09 (0.34)	1.46 (0.28)
optic flow 100% baseline speed	1.06 (0.39)	1.37 (0.26)	1.08 (0.29)	1.33 (0.30)	1.03 (0.36)	1.22 (0.48)	1.09 (0.36)	1.36 (0.28)

There was no significant interaction effect ($F_{(1,33)}$=0.074 p=0.79) between pain and audio, and no significant interaction ($F_{(1,33)}$=0.29 p=0.56) between pain and visual cues. However, there was a significant interaction ($F_{(6,198)}$=12.31 p<0.001) between audio and visual cues.

There was a significant difference between the non-pain and pain groups ($F_{(1,33)}$=8.08 p<0.01). The mean walk speed of the pain group was lower than the non-pain group across all conditions.

7.3.2 COMPARISON OF PAIN AT THE START AND END OF THE EXPERIMENT

Repeated measures analysis (paired t-test) showed no significant difference in the pain intensity (t(16 =0.46 p=0.65) or the pain affect (t(16)=2.12 p=0.05) between the beginning and end of the experiment (after 12 trials) for the pain group. Pain intensity and affect were not measured for the non-pain group (Table 7.5).

TABLE 7.5: OVERALL MEAN PAIN SCORES AT THE START AND END OF THE EXPERIMENT. PAIRED T-TEST ANALYSIS (STDEV IN BRACKETS)

	Pain intensity	**Pain affect**
Start of experiment	3.59(2.62)	2.74 (2.89)
End of experiment	3.74 (2.36)	3.26 (2.62)
	t(16) = 0.46 p=0.65	**t(16)=2.12 p=0.05**

In summary, the results support the hypothesis that audio cue tempo above baseline cadence will be associated with a significant increase in walking speed in patients with musculoskeletal pain. The results do not support the hypothesis that optic flow rate below baseline walk speed will be associated with a significant increase in walk speed, although this may be due to a limitation in the experimental design (section 7.4.1). The results do not support the hypothesis that there will be a significant difference in effect between the pain and non-pain groups. The results do not support the hypothesis that there will be a significant decrease in perceived pain when walking in treadmill-mediated VR, although it is possible that there may be an ‘effective reduction’ of pain over time (section 7.4.2).

7.4 DISCUSSION

7.4.1 THE EFFECT OF AUDIO AND VISUAL CUES ON WALK SPEED

The optic flow rate did not have the hypothesised effect on walking in either the pain or non-pain populations. If this had been just the pain group, it might have been concluded that the presence of pain was sufficient distraction to prevent a normal response to the optic flow. However, neither group demonstrated any significant effect of optic flow rate, and since this is in direct contrast to most previous studies, it warrants some examination of the experimental design. The virtual environment, screen size, treadmill type and optic flow rate were all similar to those used in the experiment in Chapter 3. However, due to the equipment constraints in the clinical laboratory, the projection was monoscopic, whereas stereoscopic projection was used in the previous experiment (chapter 3). It has already been noted that depth judgements in VR are more accurate using binocular disparity cues (section 2.2.4.3), and it may be that the lack of physiological depth cues altered the perception of the speed of optic flow, reducing the strength of its effect. A further study comparing the effect of optic flow in mono and stereo virtual environments would be required to establish if this is the cause of the unexpected result in this study. If so, it may have significant implications for virtual environment design for rehabilitation applications.

The addition of fast audio cues was associated with faster walk speeds in both pain and non-pain groups, most notably in the slow optic flow / fast audio cue combination for the non-pain group. This supports and extends the findings of the previous experiment (chapter 5), and suggests that audio cues may be effective in patients with chronic pain as well as in healthy adults. In addition, although the effect of visual cues did not reach significance level in this experiment, there was a significant interaction between the audio and visual cues, with slower walk speeds when optic flow was present compared with audio alone (no optic flow).

This might be explained by the model of competing attentional demands. Auditory and visual stimuli both require attention, which can be considered to be a finite shared resource (Eccleston & Crombez, 1999). In the presence of audio cues alone, there is sufficient attention to respond to the cues, but by adding the visual cues the attention is divided between two cues (Suteerawattananon, *et al*., 2004). Audio cues which are in conflict with the preferred cadence may disrupt the automatic synchronicity of walking, necessitating more conscious attention. The suppression of the effect of audio on walk speed by the addition of optic flow may therefore be attributable to a reduction of attention to the audio cues in the presence of a competing attentional load. However, the data in this experiment does not display a robust enough pattern to be certain of the underlying mechanisms, and further investigation is necessary to establish whether other attentional loads also reduce the influence of audio cues on walking.

Patients with pain walked on average 21% slower (1.06 m/s) across all conditions than the non-pain group (1.35 m/s). However, when the 75% or 125% audio cues were present, in the absence of optic flow, the pain group showed speed increases of up to 27% above their baseline treadmill walk speed, achieving speeds higher than the baseline treadmill walk speed of the non-pain group. This supports previous observations that individuals with pain can move faster but don't (Simmonds, *et al*., 2006).

The highest speeds found on treadmill walking (with fast audio cues) are comparable with the normal overground walking speeds recorded in Chapter 6, and indeed a paired sample t-test reveals that there is no significant difference between them (t(35)=0.85 p=0.40).

It was somewhat surprising to find that the speed increase was similar in both the slow and fast audio cue conditions. However, previous studies have noted the ability to 'double' a tempo (Styns, *et al*., 2007), and this would be consistent with the speed increase seen with this cue frequency.

7.4.2 THE EFFECT OF AUDIO AND VISUAL CUES ON PERCEIVED PAIN

The ability to disengage from pain relates to the perceived threat (Van Damme, Crombez, & Eccleston, 2004), and since patients systematically overestimate the pain associated with fast movements, this may act as a barrier to voluntary increases in speed (Simmonds, *et al*., 2006). Pain demands attention, and chronic pain involves continual switching between pain and other attentional demands (Eccleston & Crombez, 1999). Attending to the visual or auditory cues in the experiment requires attention, and if this provides a sufficient distraction to enable some disengagement from the threat of pain, then this may reduce the hindrance to faster walking. Indeed, this is supported by the finding that walk speed is higher in all cueing conditions compared with baseline.

Previous studies have demonstrated that immersive VR can reduce perceived pain during passive procedures (e.g. Gershon, *et al*., 2003; Hoffman, *et al*., 2000), and it is possible that the pain-reducing properties of VR may also be effective during active rehabilitation procedures. In total, the participants in this study undertook around 30 minutes walking, albeit in short blocks, and much of this walking was at or above the preferred (baseline) treadmill walk speed. However, there was no significant increase in reported pain intensity or pain affect. Whilst it would be anticipated that in normal treadmill walking, patients with chronic musculoskeletal pain would notice an increase in pain over time, this study did not have a control group walking on the treadmill without any audio or visual cues. To answer the question as to whether the treadmill-mediated VR suppressed the perception of increased pain, a study comparing a VR intervention with non-VR treadmill walking would be necessary.

7.5 CONCLUSION

Chronic pain (>6 months) can result in a cyclic disability-enhancing pattern of further decreased activity and avoidance that prevents normal restoration of function and perpetuates painful experiences (Hart, *et al*., 2000), and thus interventions which can distract from or reduce the perceived pain may be helpful.

Whilst treadmill-mediated VR offers recognised benefits of increased engagement and decreased pain perception (section 1.2), it does not fully overcome the slower walk speeds associated with all self-paced treadmill-based locomotor therapy. Nevertheless, the manipulation of audio and visual cues in VR does seem to offer the potential to facilitate walking, and certainly warrants further investigation.

8. CONTRIBUTION TO KNOWLEDGE

Slow walking is a common correlate of illness or injury, but often persists long after the precipitating condition has improved, and it is thought that patients could move faster but don't (Simmonds, *et al*., 2006). Since slow walking has implications for long term physical, mental and social wellbeing, it is important to find ways to address this issue.

It is well established that walking exercise programmes are one of the best approaches to increase baseline walk speed, and that these programmes are most effective if patients can be encouraged to walk at speeds above their normal preferred speed (section 1.1). For many of these patients, particularly those who cannot achieve the lowest level of community ambulation (around 0.8m/s), it is most practical to use treadmill training to achieve these walking goals. However, in spite of the evidence of the efficacy of treadmill training, adherence to therapy remains poor, and the main reason for this appears to be lack of interest and enjoyment in the exercise (section 1.1.2). Therefore a therapeutic approach which reduces the perception of pain and increases engagement in the exercise is needed.

Virtual Reality for rehabilitation is a rapidly growing area of healthcare, and treadmill-mediated VR seems to offer a potential solution to these issues of pain and lack of engagement (section 1.2). There is considerable evidence to suggest that immersion in VR can increase engagement (section 1.2.1) and decrease the perception of pain (section 1.2.2) during physical therapy. However, the question of how to encourage patients to increase their walking speed whilst interacting with virtual reality has remained unanswered. Moreover, to maximise the benefits of this type of therapy, there needs to be a greater understanding of how the components of treadmill-mediated VR can facilitate (or hinder) optimal walking.

Thus the objective of this thesis was to investigate how factors within treadmill-mediated virtual reality influence walking and perception of walking (section 1.3).

8.1 CONTRIBUTION OF THE THEORETICAL RESEARCH PROGRAMME

A virtual reality system is generally comprised of input hardware, processing software and output hardware (Figure 2.1), and these are made up of a number of subcomponents (Figure 2.2), and any of these parts may potentially influence how a user moves or perceives their movement.

Virtual reality is being used increasingly for rehabilitation, but most of the research to date has focussed on task performance and outcomes (section 1.4.1) and has paid less attention to the influence that the VR system may have on the user. Indeed, although VR is being advocated as a useful tool for movement rehabilitation (section 2.1), little or no rationale is given for the choice of software or hardware components for individual applications, and there is little research into how factors within VR may facilitate movement for rehabilitation. This makes it difficult to determine the optimum design for VR rehabilitation applications. Therefore this thesis presents the first systematic evaluation of how individual factors within virtual reality may influence walking and perception of walking (chapter 2), and, furthermore, demonstrates that these factors have a measurable and significant effect.

8.1.1 FACTORS POTENTIALLY AFFECTING WALKING AND PERCEPTION OF WALKING

Although there has been no research specifically addressing VR system design for optimal walking, there is some literature which identifies particular factors as having an effect on movement or perception, and this thesis has suggested a number of such factors which warrant further investigation; *rate of optic flow* (section 2.2.3), *visual gain* (section 2.2.3), *visual clutter* (section 2.2.2.1), *audio cue tempo* (section 2.2.2.2) and the *type of walking interface* (2.2.1.3). This is the first time that these factors have been considered together in a cohesive review.

8.1.2 FACTORS AFFECTING THE DESIGN OF VIRTUAL REALITY SYSTEMS FOR REHABILITATION

In addition to the identification of factors which require further investigation, this review also identified a number of factors for which there is already sufficient evidence that they may significantly affect movement or perception of movement; *the presence of peripheral visual cues* (section 2.2.2.1), *level of visual contrast* (section 2.2.2.1), *dimensions of objects in the virtual environment* (section 2.2.3), *field of view* (section 2.2.4.2) and *monoscopic vs. stereoscopic display* (section 2.2.4.3). This is the first review to systematically enumerate factors within a VR system which can significantly affect the movement or perception of movement of the user.

8.2 CONTRIBUTION OF THE EMPIRICAL RESEARCH PROGRAMME

8.2.1 THE MODULATING EFFECT OF OPTIC FLOW ON WALKING

The influence of optic flow on walking speed identified in section 2.2.3 suggested that manipulation of this factor may have the potential to facilitate rehabilitation goals. However, before this could be established, it was necessary to ascertain whether the modulating effects of optic flow seen in previous studies could be sustained for at least 5 minutes, in order to have a useful application in rehabilitation programmes. Therefore an experiment was conducted to address this issue (chapter 3). The results demonstrated that slow optic flow is associated with faster walking speeds, and that this effect is sustained for at least 5 minutes. This is the first study to demonstrate that the previously observed responses to optic flow could be sustained for practical application in walking rehabilitation. Additionally, it was demonstrated that faster optic flow is associated with a decrease in walking speed and this effect is also sustained for at least 5 minutes. This is important, as it is clear that the visual gain settings (and hence optic flow rates) can have a significant influence on walking speed, and this should not be ignored when designing VR applications for walking rehabilitation.

8.2.2 THE RANGE OF TOLERANCE OF VISUAL GAIN CHANGES IN VIRTUAL REALITY

The experiment in chapter 3 confirmed that reducing optic flow may be a useful tool to facilitate faster walking speeds in VR. However, section 2.2.3 identified potential issues with mis-perception of visual gain which may affect the realism or immersion of the user in the virtual environment. As the optic flow is reduced, there will come a point at which the perceived visual progression through the virtual environment is noticeably incongruent with the perceived speed of self-motion. Moreover, previous studies had observed an altered perception of the speed of optic flow when treadmill walking in a virtual environment (section 2.2.3) but had not attempted to quantify the upper and lower boundaries of perceived normal visual gain. In order to establish whether reduced optic flow (visual gain <1:1) could be tolerated as perceptually normal, an experiment was conducted to identify the range of perception of normal visual gain (chapter 4).

To achieve this, the study design did not use the standard forced-choice method of detection of a perceptual boundary, but was the first to use an approach which allowed 3 choices, enabling both upper and lower boundaries of perceived normal gain to be identified. The results demonstrated that there is a wide range of tolerance of visual gain which can be perceived as normal, but that the lower boundary of this range is higher than 1:1. This is the first study to quantify the range of tolerance of visual gain, and is the first to highlight the potential conflict between visual gain for improved walking (lower than 1:1) and visual gain for realism (greater than 1:1).

8.2.3 THE EFFECT OF AUDIO CUES ON WALKING IN VIRTUAL REALITY

The decision as to whether to use optic flow manipulation for rehabilitation in virtual reality (chapter 3) is likely to depend on a number of factors, one of which is the potential of other components of VR to offer similar benefits without the loss of visual realism (chapter 4).

Section 2.2.2.2 identified audio cue tempo as a factor with the potential to influence walk speed, but to date there has been no investigation into the effect of audio cue tempo in VR, nor on self-paced treadmill walking. Therefore an experiment was conducted to address these issues (chapter 5). The results demonstrated that audio cues at 125% of baseline walk rate are associated with an increase walking speed on a self-paced treadmill both with and without VR. This is the first study to demonstrate that audio cue tempo can have a significant influence on walk speeds on a self-paced treadmill and also in treadmill-mediated VR. This is an important finding as it highlights the fact that audio content should be considered during application design as a factor which can potentially influence the walking of the user. This is also the first study to demonstrate that, using a self-paced treadmill, the increase in walk speed is achieved by a combination of increased cadence and increased step length, allowing the natural walk ratio to be maintained as speed increases (section 5.3). This is an important finding, as treadmill gait training aims to focus on both walk speed and gait quality (section 1.1.1), and thus a mechanism which can improve gait speed without disrupting normal walk ratio could be a useful tool in rehabilitation.

In contrast, on fixed-speed treadmills, increased cadence can only be achieved by shortening the step length and thus altering the walk ratio. This supports the suggestion that self-paced treadmills allow more natural walking and are therefore better suited to rehabilitation applications of VR.

8.2.4 A COMPARISON OF OVERGROUND AND TREADMILL WALKING

Whilst it is clear from the results of the experiments in chapters 3 and 5 that it is possible to manipulate factors within VR to improve walking speed, the results also confirmed the issue of slow walking on treadmills identified in section 2.2.1.3. However, the only studies to date comparing treadmill and overground walking directly in the same population have used fixed-speed treadmills, and there is no data regarding the difference in walking on a self-paced treadmill compared with overground walking. It is important to understand how the use of a self-paced treadmill may affect walking, and therefore an experiment was conducted to compare overground and treadmill walking. The results demonstrated that self-selected walking speeds are significantly slower on a self-paced treadmill than overground, and this is true of both a healthy population and a population with chronic musculoskeletal pain. The study also demonstrated that normal walk ratios can be maintained on a self-paced treadmill, even with slower walking. This is the first study to demonstrate that users will self-select lower walking speeds on a self-paced treadmill than that selected for overground walking. This is an important finding as indiscriminate use of self-paced treadmills may lead to slower walking, potentially conflicting with the rehabilitation goals (i.e faster walking). However, this is also the first study to show that the altered walk ratio seen on fixed paced treadmills is not seen in self-paced treadmill walking, and this finding may be of significance when making a choice between fixed-speed and self-paced treadmills. A fixed-pace treadmill could enable the user to be forced to walk at a higher pace, but this is likely to cause an alteration in normal gait. On the other hand, the use of a self-paced treadmill would support more natural gait, but would necessitate the addition of other factors such as reduced optic flow (chapter 3) or fast audio cues (chapter 5) in order to facilitate an increase in walk speed. These are thus important considerations when designing a VR system for walking rehabilitation.

8.2.5 THE EFFECT OF AUDIO CUE TEMPO ON PATIENTS WITH MUSCULOSKELETAL PAIN.

It has been demonstrated that patients with musculoskeletal pain will self-select a lower walking speed when walking on a self-paced treadmill than that selected for overground walking, even though they already walk more slowly than healthy adults (chapter 6). Manipulation of the rate of optic flow and audio cues has been shown to improve walk speed in healthy adults (chapters 3 and 5) but the results cannot be assumed to be applicable to clinical populations with compromised walking. Therefore an experiment was conducted to investigate the effect of visual and audio cue tempo on patients with musculo-skeletal pain. The results demonstrated that audio cue tempo can significantly increase walk speed in patients with pain, and that the increased walk speed is not accompanied by an increase in pain. This is the first study to demonstrate that audio cueing can be effective in improving walk speed in this clinical group. The patients with pain were able to achieve walk speeds close to their overground walk speeds when walking with a fast audio cue tempo. This is an important finding as it suggests that the use of appropriate audio cues may be able to offset the lower walk speeds associated with self-paced treadmill. Thus it offers another factor for consideration to designers of virtual reality walking rehabilitation.

8.3 IMPLICATIONS FOR THE DESIGN OF VIRTUAL REALITY FOR WALKING REHABILITATION

It is important that researchers and designers become more aware of how the factors within their VR systems may impact task performance during rehabilitation, in order to design for optimal outcomes. It is clear from the findings of this theoretical and empirical research programme that there are many factors, intrinsic to the design of virtual reality for walking rehabilitation, which may influence movement and perception of movement. Identification of these factors allows a range of design decisions to be taken depending on the specific therapeutic goals (Table 8.1).

TABLE 8.1: A TOOLSET TO DETERMINE THE EFFECT OF VARIOUS VR FACTORS ON WALK SPEED, WALK RATIO; VISUAL FLOW PERCEPTION, IMMERSION AND SPACE / TRACKING REQUIREMENTS

VR factor		**Effect on walk speed**	**Effect on normal walk ratio**	**Effect on visual flow perception**	**Effect on immersion**	**Space / tracking required**
Walking interface	**Stepping in place *(section 2.2.1.2)***	N/A	Normal walking not supported	No data	Decreased immersion.	Minimal space. Steps need to be tracked
	Free walking *(section 2.2.1.2)*	Normal walk speed maintained	Normal walk ratio maintained	HMD required - see separate heading	HMD required - see separate heading	Large spaces needed. Tracking can be complex.
	Self-driven treadmill *(section 2.2.1.3)*	Baseline walk speed reduced *(Chapter 3)*	No data	Visual flow appears relatively slow *(sections 3.5 and chapter 4)*	Sense of "downhill slipping" may decrease immersion (?)	Minimal space. No tracking
	Self-paced treadmill *(section 2.2.1.3)*	Baseline walk speed reduced *(Chapter 6)*	Normal walk ratio maintained *(Chapter 6)*		More natural walking may increase immersion (?)	
	Motorised treadmill *(section 2.2.1.3)*	Walk speed pre-set by operator	Walk ratio decreased (cadence increased) *(Section 6.1.2)*		Loss of dynamic speed change may reduce immersion (?)	
Visual content	**Peripheral visual cues *(section 2.2.2.1)***	No direct effect	No direct effect	Increased accuracy of self-motion perception	No direct effect	N/A
	Correct scaling of geometry *(section 2.2.3)*	No data			Increases immersion	
	High visual contrast *(section 2.2.2.1)*	No direct effect		High contrast gives impression of faster optic flow	No direct effect	

	Visual gain ***(section 2.2.3)***	Visual gain < 1:1 increases walk speed (*) *(chapter 3)*	Lower visual gain increases stride length *(section 3.2)*	Visual gain between 1.5 and 2.4 appears realistic (*) *(chapter 4)*	Lower visual gain may decrease immersion (?)	N/A
Visual delivery	**Head mounted display** ***(section 2.2.4.1)***	No direct effect. Cautious walking more likely (?)	No direct effect	Reduced accuracy of depth and motion perception	Higher immersion	Head tracking necessary
	Large-screen display ***(sections 2.2.4.1 and 2.2.4.2)***	No direct effect. Needs to be used with stepping in place or treadmill	No direct effect	Less perceptual distortion than HMD. Wider fov possible	Less immersive than HMD	No tracking required.
	Stereoscopic projection ***(section 2.2.4.3)***	No direct effect	No direct effect	Increased accuracy of self-motion perception	Increased immersion	N/A
	Monoscopic projection ***(section 2.2.4.3)***	May reduce the effect of optic flow modulation *(chapter 7)*	No direct effect	Decreased accuracy of self-motion perception	Decreased immersion	
Audio content	**Tempo** ***(section 2.2.2.2)***	Increased walk speed with tempo 125% above baseline cadence *(chapters 5 and 7)*	Normal walk ratio maintained *(chapters 5 and 7)*	No data	No data	N/A

(*) SUBJECT TO INDIVIDUAL USER VARIATIONS

(?) FURTHER WORK REQUIRED TO CONFIRM THIS

In summary, for applications where it is important to engender a sense of slow self-speed, then optic flow manipulation would be useful for improving walk speeds. However, where visual realism is more imperative, fast audio cues can be added to the environments to improve walk speed without compromising optic flow. The use of self-paced treadmills is best suited to maintain a normal walk ratio, but is likely to be associated with overall lower walk speeds, and where this is likely to be an issue then fixed-speed treadmills could be considered as an alternative.

In addition, researchers and designers should be aware of the influence that visual clutter, visual contrast, field of view and stereoscopic display may have on task performance and user perception. Only when all these factors are taken into consideration can there be progress towards virtual reality which is designed to optimise walking performance.

8.4 FUTURE RESEARCH

Throughout this thesis, questions have been raised that require further investigation.

- Chapter 3 demonstrated that slowing the rate of optic flow leads to an increase in walk speed, and postulated that the slower optic flow may reduce the self-speed perception and hence reduce the fear of falling. Since slow walking can be a consequence of fear of falling, further investigation is suggested to establish whether slow optic flow influences fear of falling in vulnerable populations.
- Chapter 4 identified a mean value within the range of tolerance of perceived normal gain and suggested that this may be a suitable baseline gain value to suit most users. Further study is suggested to establish whether this is true, in order to better inform the calibration between treadmill input and display output.
- Chapter 5 demonstrated that an audio cue tempo 125% of baseline cadence gave rise to an increase in walk speed, but also highlighted the fact that no other fast tempos were investigated. Further work is suggested to identify the optimum audio tempo for maximum increases in walk speed.
- Furthermore, the results in chapter 5 also indicated that faster walking may also be facilitated by ‘doubling’ a slower audio cue tempo, and further investigation is required to investigate this phenomenom.
- Chapter 6 demonstrated that self-paced treadmill use is associated with slower walk speeds than overground walking, but did not identify the reasons for this. Further work is suggested in order to identify the reasons for this slowing of walk speed.
- It was also noted in chapter 6 that the experimental design may have introduced an order effect into the results, which may have had some influence on the magnitude of the effect. Further work is suggested counterbalancing the order of conditions in order to verify the initial findings.
- In addition, the overground and treadmill walk tests in chapter 6 were not of equal duration, and it is suggested that in a follow-up study both tests are of the same duration in order to verify the initial findings.
- Chapter 7 postulated that the lack of significant effect of optic flow in the experiment may be attributable to the use of monoscopic projection rather than stereoscopic projection. Further work is suggested to compare the effect of optic flow in mono and stereo environments in order to establish the relative importance of projection type when manipulating optic flow.

- Chapter 7 demonstrated that the facilitating effect of audio cues on walking appeared to be reduced in the presence of optic flow, and it was postulated that this may be due to competing attentional demands. Further work is suggested to establish whether other attentional loads also reduce the influence of audio cues on walking.
- The post-experimental levels of pain seen in the results of the experiment in chapter 7 suggest that there may have been some pain suppression in the treadmill-mediated VR. Further work is suggested comparing a VR intervention with non-VR treadmill walking to establish whether VR contributes to pain suppression when walking.

8.5 FINAL COMMENT

This thesis confirmed that small changes in factors within VR may have a significant effect on movement and movement perception. Although this thesis focussed on walking in virtual reality, it is likely that there would be similar findings relating to movement in virtual reality systems for other rehabilitation tasks, such as upper limb therapy.

In studying the factors which influence walking and perception of walking in treadmill-mediated virtual reality (section 1.3), this thesis both identified a number of directions for further research (section 8.4) and also contributed significant new knowledge which may help inform and improve the design of virtual reality systems for rehabilitation (chapters 3, 4, 5, 6 and 7, section 8.2).

9. REFERENCES

Ada, L., Dean, C. M., Hall, J. M., Bampton, J., & Crompton, S. (2003). A treadmill and overground walking program improves walking in persons residing in the community after stroke: a placebo-controlled, randomized trial. *Arch Phys Med Rehabil, 84*(10), 1486-1491.

Ada, L., Dean, C. M., Lindley, R., & Lloyd, G. (2009). Improving community ambulation after stroke: the AMBULATE trial. *BMC Neurology, 9*(1), 8.

Adamovich, S. V., Merians, A. S., Boian, R., Lewis, J. A., Tremaine, M., Burdea, G. S., *et al*. (2005). A virtual reality-based exercise system for hand rehabilitation post-stroke. [Article]. *Presence-Teleoperators and Virtual Environments, 14*(2), 161-174.

Ahmaniemi, T. (2007). *Influence of tempo and subjective rating of music in step frequency of running.* Paper presented at the 8th International Conference on Music Information Retrieval, Vienna, Austria.

Alm, P. A. (2004). Stuttering and the basal ganglia circuits: a critical review of possible relations. *J Commun Disord, 37*(4), 325-369.

Alton, F., Baldey, L., Caplan, S., & Morrissey, M. C. (1998). A kinematic comparison of overground and treadmill walking. *Clinical Biomechanics, 13*(6), 434-440.

Angelaki, D. E., & Cullen, K. E. (2008). Vestibular System: The Many Facets of a Multimodal Sense. *Annual Review of Neuroscience, 31*(1), 125-150.

Anton, R., Opris, D., Dobrean, A., David, D., & Rizzo, A. (2009). *Virtual reality in rehabilitation of attention deficit / hyperactivity disorder The instrument construction principles.* Paper presented at the Virtual Rehabilitation International Conference, 2009.

Apfelbaum, H., Pelah, A., & Peli, E. (2007). Heading assessment by “tunnel vision” patients and control subjects standing or walking in a virtual reality environment. *ACM Trans. Appl. Percept., 4*(1), 8.

Banton, T., Stefanucci, J., Durgin, F., Fass, A., & Proffitt, D. (2005). The Perception of Walking Speed in a Virtual Environment. *Presence: Teleoperators & Virtual Environments, 14*(4), 394-406.

Banton, T. A., Steve, J., Durgin, F. H., & Proffitt, D. R. (2000). The calibration of optic flow and treadmill speed during treadmill walking in a virtual environment. *Investigative Ophthalmology and Visual Science, 41*(4), S718.

Bardorfer, A., Munih, M., Zupan, A., & Primozic, A. (2001). Upper limb motion analysis using haptic interface. [Article]. *Ieee-Asme Transactions on Mechatronics, 6*(3), 253-260.

Biderman, A., Cwikel, J., Fried, A. V., & Galinsky, D. (2002). Depression and falls among community dwelling elderly people: a search for common risk factors. *Journal of Epidemiology and Community Health, 56*(8), 631-636.

Boian, R. F., Burdea, G. C., Deutsch, J. E., & Winter, S. H. (2004). *Street crossing using a virtual environment mobility simulator.* Paper presented at the IWVR 2004, Lausanne, Switzerland.

Broeren, J., Rydmark, M., & Sunnerhagen, K. S. (2004). Virtual reality and haptics as a training device for movement rehabilitation after stroke: A single-case study. *Archives of Physical Medicine and Rehabilitation, 85*(8), 1247-1250.

Bryanton, C., Bosse, J., Brien, M., McLean, J., McCormick, A., & Sveistrup, H. (2006). Feasibility, motivation, and selective motor control: virtual reality compared to conventional home exercise in children with cerebral palsy. *CyberPsychology and Behavior, 9*(2), 123-128.

Burdea, G., Deshpande, S., Langrana, N., Gomez, D., & Liu, B. (1997). A virtual reality-based system for hand diagnosis and rehabilitation. [Article]. *Presence-Teleoperators and Virtual Environments, 6*(2), 229-240.

Burdea, G., Popescu, V., Hentz, V., & Colbert, K. (2000). Virtual reality-based orthopedic telerehabilitation. [Article]. *Ieee Transactions on Rehabilitation Engineering, 8*(3), 430-432.

Chamberlin, M. E., Fulwider, B. D., Sanders, S. L., & Medeiros, J. M. (2005). Does Fear of Falling Influence Spatial and Temporal Gait Parameters in Elderly Persons Beyond Changes Associated With Normal Aging? *J Gerontol A Biol Sci Med Sci, 60*(9), 1163-1167.

Chang, Y.-J., Chen, S.-F., & Huang, J.-D. (2011). A Kinect-based system for physical rehabilitation: A pilot study for young adults with motor disabilities. *Research in Developmental Disabilities*

Cluss, M. B., Crane, E. A., Gross, M. M., & Frederickson, B. L. (2006, September 6-9). *Effect of emotion on the kinematics of gait.* Paper presented at the American Society of Biomechanics, Blacksburg, VA.

Craig, A. B., Sherman, W. R., & Will, J. D. (2009). *Developing Virtual Reality Applications*: Morgan Kaufmann.

Creem-Regehr, S. H., Willemsen, P., Gooch, A. A., & Thompson, W. B. (2005). The influence of restricted viewing conditions on egocentric distance perception: Implications for real and virtual indoor environments. *Perception, 34*(2), 191-204.

del Olmo, M. F., Arias, P., Furio, M. C., Pozo, M. A., & Cudeiro, J. (2006). Evaluation of the effect of training using auditory stimulation on rhythmic movement in Parkinsonian patients--a combined motor and [18F]-FDG PET study. *Parkinsonism & Related Disorders, 12*(3), 155-164.

Deutsch, J. E., Latonio, J., Burdea, G. C., & Boian, R. (2001). Post-stroke rehabilitation with the Rutgers Ankle system: A case study. [Article]. *Presence-Teleoperators and Virtual Environments, 10*(4), 416-430.

Dietz, V. (2002). Proprioception and locomotor disorders. *Nat Rev Neurosci, 3*(10), 781-790.

Distler, H. K., Pelah, A., Bell, A. G., & Thurrell, A. E. I. (1998). *The perception of absolute speed during self-motion (abstract).* Paper presented at the European conference on visual perception, Oxford, UK.

Duffy, C. J. (1998). MST neurons respond to optic flow and translational movement. *J Neurophysiol, 80*(4), 1816-1827.

Dumurgier, J., Elbaz, A., Ducimetiere, P., Tavernier, B., Alperovitch, A., & Tzourio, C. (2009). Slow walking speed and cardiovascular death in well functioning older adults: prospective cohort study. *BMJ,* 339: b4460

Durgin, F., Reed, C., & Tigue, C. (2007). Step frequency and perceived self-motion. *ACM Trans. Appl. Percept., 4*(1), 5.

Durgin, F. H., Fox, L. F., Schaffer, E., & Whitaker, R. (2005). *The perception of linear self-motion.* Paper presented at the Proceedings of SPIE, San Jose, California.

Durgin, F. H., Gigone, K., & Scott, R. (2005). Perception of visual speed while moving. *J Exp Psychol Hum Percept Perform, 31*(2), 339-353.

Durgin, F. H., Pelah, A., Fox, L. F., Lewis, J., Kane, R., & Walley, K. A. (2005). Self-motion perception during locomotor recalibration: more than meets the eye. *J Exp Psychol Hum Percept Perform, 31*(3), 398-419.

Durgin, F. H., Proffitt, D. R., Olson, T. J., & Reinke, K. S. (1995). Comparing depth from motion with depth from binocular disparity. *J Exp Psychol Hum Percept Perform, 21*(3), 679-699.

Eccleston, C., & Crombez, G. (1999). Pain Demands Attention: A Cognitive-Affective Model of the Interruptive Function of Pain. *Psychological Bulletin, 125*(3), 356-366.

Enright, P. L. (2003). The six-minute walk test. *Respiratory Care, 48*, 783-785.

Ferrell, B. A., Josephson, K. R., Pollan, A. M., Loy, S., & Ferrell, B. R. (1997). A randomized trial of walking versus physical methods for chronic pain management. *Aging (Milano), 9*(1-2), 99-105.

Ford, M. P., Wagenaar, R. C., & Newell, K. M. (2007). The effects of auditory rhythms and instruction on walking patterns in individuals post stroke. *Gait & Posture, 26*(1), 150-155.

Forkan, R., Pumper, B., Smyth, N., Wirkkala, H., Ciol, M. A., & Shumway-Cook, A. (2006). Exercise Adherence Following Physical Therapy Intervention in Older Adults With Impaired Balance. *PHYS THER, 86*(3), 401-410.

Frenz, H., Lappe, M., Kolesnik, M., & Buhrmann, T. (2007). Estimation of travel distance from visual motion in virtual environments. *ACM Trans. Appl. Percept., 4*(1), 3.

Fung, J., Malouin, F., McFadyen, B. J., Comeau, F., Lamontagne, A., Chapdelaine, S., *et al*. (2004). Locomotor rehabilitation in a complex virtual environment. *Conf Proc IEEE Eng Med Biol Soc, 7*, 4859-4861.

Fung, J., Malouin, F., McFadyen, B. J., Comeau, F., Lamontagne, A., Chapdelaine, S., *et al*. (2004b). *Locomotor rehabilitation in a complex virtual environment*.

Fung, J., Richards, C. L., Malouin, F., McFadyen, B. J., & Lamontagne, A. (2006). A treadmill and motion coupled virtual reality system for gait training post-stroke. [Article]. *Cyberpsychology & Behavior, 9*(2), 157-162.

Gardner, A. W., & Poehlman, E. T. (1995). Exercise Rehabilitation Programs for the Treatment of Claudication Pain. *JAMA: The Journal of the American Medical Association, 274*(12), 975-980.

Gershon, J., Zimand, E., Lemos, R., Rothbaum, B. O., & Hodges, L. (2003). Use of Virtual Reality as a Distractor for Painful Procedures in a Patient with Pediatric Cancer: A Case Study. *CyberPsychology & Behavior, 6*(6), 657-661.

Girone, M., Burdea, G., Bouzit, M., Popescu, V., & Deutsch, J. E. (2001). A stewart platform-based system for ankle telerehabilitation. [Article]. *Autonomous Robots, 10*(2), 203-212.

Godefroy, O., Spagnolo, S., Roussel, M., & Boucart, M. (2010). Stroke and Action Slowing: Mechanisms, Determinants and Prognosis Value. *Cerebrovascular Diseases, 29*(5), 508-514.

Gold, J. I., Belmont, K. A., & Thomas, D. A. (2007). The neurobiology of virtual reality pain attenuation. *Cyberpsychol Behav, 10*(4), 536-544.

Graham, J. E., Fisher, S. R., Berges, I. M., Kuo, Y. F., & Ostir, G. V. (2010). Walking speed threshold for classifying walking independence in hospitalized older adults. *PHYS THER, 90*(11), 1591-1597.

Grigsby, J., Rosenberg, N. L., & Busenbark, D. (1995). Chronic pain is associated with deficits in information processing. *Percept Mot Skills, 81*(2), 403-410.

Gu, Y., Angelaki, D. E., & DeAngelis, G. C. (2008). Neural correlates of multisensory cue integration in macaque MSTd. *Nat Neurosci, 11*(10), 1201-1210.

Hardage, J., Peel, C., Morris, D., Graham, C., Brown, C., Foushee, H. R., *et al*. (2007). Adherence to Exercise Scale for Older Patients (AESOP): a measure for predicting exercise adherence in older adults after discharge from home health physical therapy. *J Geriatr Phys Ther, 30*(2), 69-78.

Harris, L. R., Jenkin, M., & Zikovitz, D. C. (2000). Visual and non-visual cues in the perception of linear self-motion. *Exp Brain Res, 135*(1), 12-21.

Harris, M. (2002). Motion Vision. In D. Roberts (Ed.), *Signals and Perception: The fundamentals of human sensation* (pp. 199-209). Basingstoke, UK: Palgrave Macmillan.

Hart, R. P., Martelli, M. F., & Zasler, N. D. (2000). Chronic Pain and Neuropsychological Functioning. *Neuropsychology Review, 10*(3), 131-149.

Harwood, R. H., & Conroy, S. P. (2009). Slow walking speed in elderly people. *BMJ,* 339:b4236

Hendry, M., Williams, N. H., Markland, D., Wilkinson, C., & Maddison, P. (2006). Why should we exercise when our knees hurt? A qualitative study of primary care patients with osteoarthritis of the knee. *Fam. Pract., 23*(5), 558-567.

Hoffman, H., G., Richards, T.L., Coda, B., Bills, A.R., Blough, D., Richards, A.L., Sharar, S.R. (2004). Modulation of thermal pain-related brain activity with virtual reality: evidence from fMRI. *Neuroreport, 15*(8), 1245-1248.

Hoffman, H. G., Doctor, J. N., Patterson, D. R., Carrougher, G. J., & Furness, T. A., 3rd. (2000). Virtual reality as an adjunctive pain control during burn wound care in adolescent patients. *Pain, 85*(1-2), 305-309.

Hoffman, H. G., Garcia-Palacios, A., Kapa, V., Beecher, J., & Sharar, S. R. (2003). Immersive Virtual Reality for Reducing Experimental Ischemic Pain. *International Journal of Human-Computer Interaction, 15*(3), 469-486.

Hoffman, H. G., Patterson, D. R., & Carrougher, G. J. (2000). Use of Virtual Reality for Adjunctive Treatment of Adult Burn Pain During Physical Therapy: A Controlled Study. *The Clinical Journal of Pain, 16*(3), 244-250.

Hoffman, H. G., Patterson, D. R., Carrougher, G. J., Nakamura, D., Moore, M., Garcia-Palacios, A., *et al*. (2001). The Effectiveness of Virtual Reality Pain Control With Multiple Treatments of Longer Durations: A Case Study. *International Journal of Human-Computer Interaction, 13*(1), 1-12.

Holden, M. K. (2005). Virtual environments for motor rehabilitation: review. *Cyberpsychol Behav, 8*(3), 187-211; discussion 212-189.

Jack, D., Boian, R., Merians, A. S., Tremaine, M., Burdea, G. C., Adamovich, S. V., *et al*. (2001). Virtual reality-enhanced stroke rehabilitation. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on [see also IEEE Trans. on Rehabilitation Engineering], 9*(3), 308-318.

JudgeRoy, J. O., Davis, B., & Õunpuu, S. (1996). Step Length Reductions in Advanced Age: The Role of Ankle and Hip Kinetics. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 51A*(6), M303-M312.

Jylha, M., Guralnik, J. M., Balfour, J., & Fried, L. P. (2001). Walking Difficulty, Walking Speed, and Age as Predictors of Self-Rated Health: The Women's Health and Aging Study. *J Gerontol A Biol Sci Med Sci, 56*(10), M609-617.

Karageorghis, C. I., Mouzourides, D. A., Priest, D., Sasso, T. A., Morrish, D. J., & Walley, C. L. (2009). Psychophysical and ergogenic effects of synchronous music during treadmill walking. *Journal of Sport & Exercise Psychology, 31*, 18-36.

Karageorghis, C. I., & Terry, P. C. (1997). The psychophysical effects of music in sport and exercise: a review. *Journal of Sport Behaviour, 20*, 54-69.

Kassler, L., Feasel, J., Lewek, M. D., Frederick P. Brooks, J., & Whitton, M. C. (2010). *Matching actual treadmill walking speed and visually perceived walking speed in a projection virtual environment*. Paper presented at the Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization.

Kearns, M., Durgin, F. H., & Warren, W. (2002). Sensitivity to the gain of optic flow during walking. *Journal of Vision, 2*(7), 431-431.

Keefe, F. J., & Hill, R. W. (1985). An objective approach to quantifying pain behavior and gait patterns in low back pain patients. *Pain, 21*(2), 153-161.

Kim, G. J. (2005). *Designing Virtual Reality Systems*. London: Springer-Verlag.

Kizony, R., Katz, N., & Weiss, P. L. (2003). Adapting an immersive virtual reality system for rehabilitation. [Article]. *Journal of Visualization and Computer Animation, 14*(5), 261-268.

Kizony, R., Raz, L., Katz, N., Weingarden, H., & Weiss, P. L. T. (2005). Video-capture virtual reality system for patients with paraplegic spinal cord injury. [Article]. *Journal of Rehabilitation Research and Development, 42*(5), 595-607.

Kleiber, C., & Harper, D. C. (1999). Effects of Distraction on Children's Pain and Distress During Medical Procedures: A Meta-Analysis. *Nursing Research, 48*(1), 44-49.

Knoblauch, R. L., Pietrucha, M. P., & Nitzburg, M. (1996). Field Studies of Pedestrian Walking Speed and Start-Up Time. *Transportation Research Record, 1538*, 27-38.

Konczak, J. (1994). Effects of optic flow on the kinematics of human gait: a comparison of young and older adults. *Journal of Motor Behaviour, 26*(3), 225-236.

Kuys, S. S., Bew, P. G., Lynch, M. R., Morrison, G., & Brauer, S. G. (2009). Measures of activity limitation on admission to rehabilitation after stroke predict walking speed at discharge: an Observational study. *Australian Journal of Physiotherapy, 55*(4), 265-268.

Lamontagne, A., & Fung, J. (2004). Faster is better: implications for speed-intensive gait training after stroke. *Stroke, 35*(11), 2543-2548.

Lamoth, C., Stins, J., Pont, M., Kerckhoff, F., & Beek, P. (2008). Effects of attention on the control of locomotion in individuals with chronic low back pain. *Journal of Neuroengineering and rehabilitation, 5*(1), 13.

Laufer, Y., Dickstein, R., Chefez, Y., & Marcovitz, E. (2001). The effect of treadmill training on the ambulation of stroke survivors in the early stages of rehabilitation: a randomized study. *J Rehabil Res Dev, 38*(1), 69-78.

Lee, S. J., & Hidler, J. (2008). Biomechanics of overground vs. treadmill walking in healthy individuals. *J Appl Physiol, 104*(3), 747-755.

Lichtenstein, L., Barabas, J., Woods Russell, L., & Peli, E. (2007). A feedback-controlled interface for treadmill locomotion in virtual environments. *ACM Trans. Appl. Percept., 4*(1), 7.

Lim, I., van Wegen, E., de Goede, C., Deutekom, M., Nieuwboer, A., Willems, A., *et al*. (2005). Effects of external rhythmical cueing on gait in patients with Parkinson's disease: a systematic review. *Clinical Rehabilitation, 19*(7), 695-713.

Loomis, J. M., Blascovich, J. J., & Beall, A. C. (1999). Immersive virtual environment technology as a basic research tool in psychology. *Behav Res Methods Instrum Comput, 31*(4), 557-564.

Lord, S. E., McPherson, K., McNaughton, H. K., Rochester, L., & Weatherall, M. (2004). Community ambulation after stroke: how important and obtainable is it and what measures appear predictive? *Archives of Physical Medicine and Rehabilitation, 85*(2), 234-239.

Luft, A. R., Macko, R. F., Forrester, L. W., Villagra, F., Ivey, F., Sorkin, J. D., *et al*. (2008). Treadmill Exercise Activates Subcortical Neural Networks and Improves Walking After Stroke. A Randomized Controlled Trial. *Stroke*, STROKEAHA.108.527531.

Luukinen, H., Koski, K., Laippala, P., & Kivela, S.-L. (1995). Predictors for recurrent falls among the home-dwelling elderly. *Scandinavian Journal of Primary Health Care, 13*(4), 294-299.

MacDougall, H. G., & Moore, S. T. (2005). Marching to the beat of the same drummer: the spontaneous tempo of human locomotion. *J Appl Physiol, 99*(3), 1164-1173.

Magnenat-Thalman, N., Kim, H., Egges, A., & Garchery, S. (2005). *Believability and interaction in virtual worlds.* Paper presented at the Multimedia Modelling Conference (MMM'05).

Mayer, D. J., Wolfle, T. L., Akil, H., Carder, B., & Liebeskind, J. C. (1971). Analgesia from Electrical Stimulation in the Brainstem of the Rat. *Science, 174*(4016), 1351-1354.

McCaffrey, M., & Beebe, A. (1993). *Pain: Clinical Manual for Nursing Practice*. Baltimore: V.V. Mosby Company.

McIntosh, G. C., Brown, S. H., Rice, R. R., & Thaut, M. H. (1997). Rhythmic auditory-motor facilitation of gait patterns in patients with Parkinson's disease. *Journal of neurology, neurosurgery, and psychiatry, 62*(1), 22-26.

Melzack, R., & Wall, P. D. (1965). Pain mechanisms: a new theory. *Science, 150*(699), 971-979.

Menz, H. B., Lord, S. R., & Fitzpatrick, R. C. (2003). Agerelated differences in walking stability. *Age and Ageing, 32*(2), 137-142.

Merians, A. S., Jack, D., Boian, R., Tremaine, M., Burdea, G. C., Adamovich, S. V., *et al*. (2002). Virtual reality-augmented rehabilitation for patients following stroke. [Article]. *Physical Therapy, 82*(9), 898-915.

Mohler, B. J., Thompson, W. B., Creem-Regehr, S., Pick, H. L., Warren, W., Rieser, J. J., *et al*. (2004). *Visual motion influences locomotion in a treadmill virtual environment.* Paper presented at the Proceedings of the 1st symposium on applied perception in graphics and visualization, Los Angeles, California.

Mohler, B. J., Thompson, W. B., Creem-Regehr, S. H., Willemsen, P., Pick Jr, H. L., & Rieser, J. J. (2007). Calibration of locomotion resulting from visual motion in a treadmill-based virtual environment. *ACM Trans. Appl. Percept., 4*(1), 4.

Monen, J., & Brenner, E. (1994). Detecting changes in one's own velocity from the optic flow. *Perception, 23*(6), 681-690.

Morris, R. G. (2005). Commentary on Rose, F.D., Brooks, B.M., & Rizzo, A.A., virtual reality in brain damage rehabilitation: Review. [Editorial Material]. *Cyberpsychology & Behavior, 8*(3), 267-268.

Murray, M. P., Sepic, S. B., Gardner, G. M., & Downs, W. J. (1978). Walking patterns of men with parkinsonism. *Am J Phys Med, 57*(6), 278-294.

Neth, C. T., Souman, J. L., Engel, D., Klos, U., Bulthoff, H. H., & Mohler, B. J. (2011). *Velocity-Dependent Dynamic Curvature Gain for Redirected Walking.* Paper presented at the IEEE VR, Singapore.

Neyer, J. R., Greenlund, K. J., Denny, C. H., Keenan, N. L., Casper, M., Labarthe, D. R., *et al*. (2007). Prevalence of Stroke - United States 2005. *Morbidity and mortality weekly report*,

Pailhous, J., Ferrandez, A. M., Fluckiger, M., & Baumberger, B. (1990). Unintentional modulations of human gait by optical flow. *Behav Brain Res, 38*(3), 275-281.

Palmisano, S. (1996). Perceiving self-motion in depth: the role of stereoscopic motion and changing-size cues. *Perception and psychophysics, 58*(8), 1168-1176.

Peck, T., Fuchs, H., & Whitton, M. C. (2011). *An Evaluation of Navigational Ability Comparing Redirected Free Exploration with Distractors to Walking-in-Place and Joystick locomotion Interfaces.* Paper presented at the IEEE VR, Singapore.

Piron, L., Tonin, P., Piccione, F., Iaia, V., Trivello, E., & Dam, M. (2005). Virtual environment training therapy for arm motor rehabilitation. [Article]. *Presence-Teleoperators and Virtual Environments, 14*(6), 732-740.

Pohl, M., Mehrholz, J., Ritschel, C., & Ruckriem, S. (2002). Speed-dependent treadmill training in ambulatory hemiparetic stroke patients: a randomized controlled trial. *Stroke, 33*(2), 553-558.

Pohl, M., Rockstroh, G., Ruckriem, S., Mrass, G., & Mehrholz, J. (2003). Immediate effects of speed-dependent treadmill training on gait parameters in early Parkinson's disease. *Arch Phys Med Rehabil, 84*(12), 1760-1766.

Powell, W., Hand, S., Stevens, B., & Simmonds, M. J. (2006). Optic Flow with a Stereoscopic Display: Sustained Influence on Speed of Locomotion. *Annual Review of CyberTherapy and Telemedicine, 4*, 65-70.

Powell, W., & Simmonds, M. (2008). Editorial: Virtual reality: A healthy perspective. [Editorial]. *International Journal of Therapy and Rehabilitation, 15*(11), 480-481.

Powell, W., Stevens, B., Hand, S., & Simmonds, M. (2010). Sounding Better: Fast Audio Cues Increase Walk Speed in Treadmill-Mediated Virtual Rehabilitation Environments. *Studies in Health Technology and Informatics, 154*, 202-207.

Powell, W., Stevens, B., Hand, S., & Simmonds, M. (2011). *Blurring the Boundaries: The Perception of Visual Gain in Treadmill-Mediated Virtual Environments* Paper presented at the Workshop on Perceptual Illusion in Virtual Environments (IEEEVR), Singapore.

Powell, W., Stevens, B., Hand, S., & Simmonds, M. J. (2007). Software Gearing in a Virtual Environment: The Effect on Perception of Optic Flow. *Annual Review of CyberTherapy and Telemedicine, 5*, 99-106.

Powell, W., Stevens, B., Hand, S., & Simmonds, M. J. (2008). *The influence of visual and auditory cues on pain and movement in a treadmill-mediated virtual environment..* Paper presented at the Pain, Mind and Movement II - An Official Satellite Symposium of the XIIth World Congress on Pain., Dublin, Ireland.

Powell, W., Stevens, B., & Simmonds, M. (2009). Treadmill Interface for Virtual Reality vs. Overground Walking: A Comparison of Gait in Individuals with and without Pain. *Studies in Health Technology and Informatics, 144*, 198-203.

Prokop, T., Schubert, M., & Berger, W. (1997). Visual influence on human locomotion. Modulation to changes in optic flow. *Exp Brain Res, 114*(1), 63-70.

Rand, D., Kizony, R., & Weiss, P. L. (2004). *Virtual reality rehabilitation for all: Vivid GX versus Sony PlayStation II EyeToy.* Paper presented at the 5th Intl Conf. Disability, Virtual Reality & Assoc. Tech, Oxford, UK.

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin & Review, 12*(6), 969-992.

Resnick, B., Orwig, D., D'Adamo, C., Yu-Yahiro, J., Hawkes, W., Shardell, M., *et al*. (2007). Factors that influence exercise activity among women post hip fracture participating in the Exercise Plus Program. *Clin Interv Aging, 2*(3), 413-427.

Riecke, B. E., Schulte-Pelkum, J., & Bulthoff, H. H. (2005). *Perceiving simulated ego-motions in Virtual Reality - comparing large screen displays with HMD's*. Paper presented at the Proceedings of SPIE.

Rizzo, A., & Kim, G. J. (2005). A SWOT analysis of the field of virtual reality rehabilitation and therapy. [Article]. *Presence-Teleoperators and Virtual Environments, 14*(2), 119-146.

Roerdink, M., Lamoth, C. J. C., Kwakkel, G., van Wieringen, P. C. W., & Beek, P. J. (2007). Gait Coordination After Stroke: Benefits of Acoustically Paced Treadmill Walking. *PHYS THER, 87*(8), 1009-1022.

Rota, V., Perucca, L., Simone, A., & Tesio, L. (2011). Walk ratio (step length/cadence) as a summary index of neuromotor control of gait: application to multiple sclerosis. *International Journal of Rehabilitation Research, EPublish Ahead of Print*

Schubert, M., Prokop, T., Brocke, F., & Berger, W. (2005). Visual kinesthesia and locomotion in Parkinson's disease. *Mov Disord, 20*(2), 141-150.

Sekiya, N., & Nagasaki, H. (1998). Reproducibility of the walking patterns of normal young adults: test-retest reliability of the walk ratio(step-length/step-rate). *Gait & Posture, 7*(3), 225-227.

Sharrack, B., & Hughes, R. A. C. (1997). Reliability of distance estimation by doctors and patients: cross sectional study. *BMJ, 315*(7123), 1652-1654.

Silver, K. H., Macko, R. F., Forrester, L. W., Goldberg, A. P., & Smith, G. V. (2000). Effects of aerobic treadmill training on gait velocity, cadence, and gait symmetry in chronic hemiparetic stroke: a preliminary report. *Neurorehabil Neural Repair, 14*, 65 - 71.

Simmonds, M. J., Goubert, L., Moseley, G. L., & Verbunt, J. A. (2006). *Moving with Pain.* Paper presented at the Proceedings of the 11th World Congress on Pain, Seattle, WA.

Slater, M., Usoh, M., & Steed, A. (1995). Taking Steps: The Influence of a Walking Technique on Presence in Virtual Reality. *ACM Transactions on Comupter-Human Interaction, 2*(3), 201-219.

Stanney, K. M. (Ed.). (2002). *Handbook of Virtual Environments*. London: Lawrence Erlbaum.

Stolze, H., Kuhtz-Buschbeck, J. P., Mondwurf, C., Boczek-Funcke, A., Jöhnk, K., Deuschl, G., *et al*. (1997). Gait analysis during treadmill and overground locomotion in children and adults. *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control, 105*(6), 490-497.

Stone, L. S., & Thompson, P. (1992). Human speed perception is contrast dependent. *Vision Res, 32*(8), 1535-1549.

Styns, F., van Noorden, L., Moelants, D., & Leman, M. (2007). Walking on music. *Human Movement Science, 26*(5), 769-785.

Sullivan, K. J., Knowlton, B. J., & Dobkin, B. H. (2002). Step training with body weight support: effect of treadmill speed and practice paradigms on poststroke locomotor recovery. *Arch Phys Med Rehabil, 83*(5), 683-691.

Suma, E. A., Clark, S., Finkelstein, S., Wartell, Z., Krum, D., & Bolas, M. (2011). *Leveraging Change Blindness for Redirection in Virtual Environments.* Paper presented at the IEEE VR, Singapore.

Sun, H. J., Lee, A. J., Campos, J. L., Chan, G. S., & Zhang, D. H. (2003). Multisensory integration in speed estimation during self-motion. *Cyberpsychol Behav, 6*(5), 509-518.

Suteerawattananon, M., Morris, G. S., Etnyre, B. R., Jankovic, J., & Protas, E. J. (2004). Effects of visual and auditory cues on gait in individuals with Parkinson's disease. *Journal of the Neurological Sciences, 219*(2), 63-69.

Sveistrup, H. (2004). Motor rehabilitation using virtual reality. *J Neuroengineering Rehabil, 1*(1), 10.

Sveistrup, H., McComas, J., Thornton, M., Marshall, S., Finestone, H., McCormick, A., *et al*. (2003). Experimental studies of virtual reality-delivered compared to conventional exercise programs for rehabilitation. *Cyberpsychol Behav, 6*(3), 245-249.

Teasell, R., Foley, N., Salter, K., Bhogal, S., Bayona, N., Jutai, J., *et al*. (2006). *Evidence-based review of stroke rehabilitation*.

Templeman, J. N., Denbrook, P. S., & Sibert, L. E. (1999). Virtual Locomotion: Walking in Place through Virtual Environments. *Presence: Teleoperators & Virtual Environments, 8*(6), 598-617.

Thaut, M. H., Kenyon, G. P., Schauer, M. L., & McIntosh, G. C. (1999). The connection between rhythmicity and brain function. *Engineering in Medicine and Biology Magazine, IEEE, 18*(2), 101-108.

Thaut, M. H., McIntosh, G. C., Rice, R. R., Miller, R. A., Rathbun, J., & Brault, J. M. (1996). Rhythmic auditory stimulation in gait training for Parkinson's disease patients. *Mov Disord, 11*(2), 193-200.

Thornton, M., Marshall, S., McComas, J., Finestone, H., McCormick, A., & Sveistrup, H. (2005). Benefits of activity and virtual reality based balance exercise programmes for adults with traumatic brain injury: Perceptions of participants and their caregivers. [Article]. *Brain Injury, 19*(12), 989-1000.

Thurrell, A., & Pelah, A. (2005). *Matching visual and nonvisual signals: evidence for a mechanism to discount optic flow during locomotion.* Paper presented at the Human Vision and Electronic Imaging X, San Jose, Ca.

Thurrell, A. E. I., & Pelah, A. (2002). Reduction of perceived visual speed during walking: Effect dependent upon stimulus similarity to the visual consequences of locomotion. *Journal of Vision, 2*(7), 628-628.

Truong, P. T., Gaul, C. A., McDonald, R. E., Petersen, R. B., Jones, S. O., Alexander, A. S., *et al*. (2011). Prospective Evaluation of a 12-Week Walking Exercise Program and Its Effect on Fatigue in Prostate Cancer Patients Undergoing Radical External Beam Radiotherapy. *American Journal of Clinical Oncology, 34*(4)

Usoh, M., Arthur, K., Whitton Mary, C., Bastos, R., Steed, A., Slater, M., *et al*. (1999). *Walking > walking-in-place > flying, in virtual environments*. Paper presented at the Proceedings of the 26th annual conference on Computer graphics and interactive techniques.

Valkovič, P., Krafczyk, S., šaling, M., Benetin, J., & Bötzel, K. (2006). Postural reactions to neck vibration in Parkinson's disease. *Movement Disorders, 21*(1), 59-65.

Van Damme, S., Crombez, G., & Eccleston, C. (2004). Disengagement from pain: the role of catastrophic thinking about pain. *Pain, 107*(1-2), 70-76.

van Noorden, L., & Moelants, D. (1999). Resonance in the Perception of Musical Pulse. *Journal of New Music Research, 28*, 43-66.

Varraine, E., Bonnard, M., & Pailhous, J. (2002). Interaction between different sensory cues in the control of human gait. *Experimental Brain Research, 142*, 374-384.

Viau, A., Feldman, A. G., McFadyen, B. J., & Levin, M. F. (2004). Reaching in reality and virtual reality: a comparison of movement kinematics in healthy subjects and adults with hemiparesis. *Journal of Neuroengineering and rehabilitation, 1*(11).

Warren, P. A., & Rushton, S. K. (2007). Perception of object trajectory: Parsing retinal motion into self and object movement components. *Journal of Vision, 7*(11), 1-11.

Warren, W. H., Jr., Kay, B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nat Neurosci, 4*(2), 213-216.

Wolpert, D. M., & Flanagan, J. R. (2001). Motor Prediction. *Current Biology, 11*, R729-R732.

You, S. H., Jang, S. H., Kim, Y. H., Hallett, M., Ahn, S. H., Kwon, Y. H., *et al*. (2005). Virtual reality-induced cortical reorganization and associated locomotor recovery in chronic stroke - An experimenter-blind randomized study. [Article]. *Stroke, 36*(6), 1166-1171.

Zielinski, D. J., McMahan, R. P., & Brady, R. B. (2011). *Shadow Walking: an Unencumbered Locomotion Technique for Systems with Under-floor Projection.* Paper presented at the IEEE VR, Singapore.

Zijlstra, A., de Bruin, E. D., Bruins, N., & Zijlstra, W. (2008). The step length-frequency relationship in physically active community-dwelling older women. *Eur J Appl Physiol, 104*(3), 427-434.

GLOSSARY

- ***ADL (activities of daily living)*** - Carrying out simple or complex and coordinated actions in order to complete the requirements of day-to-day procedures or duties.
- ***Audio cue tempo*** - the rate at which a sound is repeated, measured in beats/s
- ***Audio cueing*** – providing an external repeating audio signal in order to promote or facilitate motor behaviour such as walking
- ***Back projection*** – the projector is behind the screen which diffusely transmits the light through. This projection method is often preferred in VR as it reduces the likelihood of occlusion of the on-screen image by the user.
- ***Body-weight support*** - a mechanical system which takes some or all of a patient's body-weight, to provide stability and to enable gradual progression of weight bearing according to the needs of the patient.
- ***Cadence (step frequency)*** - the frequency of individual steps from heel-strike on one foot to heel-strike on the other foot, often measured in steps/s
- ***Gain matching*** - identifying an optic flow speed which is perceptually matched to the kinaesthetic estimate of self motion. For example 'correct' gain matching would recognise that a self-speed of 1m/s relates to an optic flow speed of 1m/s.
- ***Gait -*** The pattern of stepping and walking specific to an individual. Different gaits are characterized by differences in step length, step frequency, step symmetry, velocity, changes in the contact with the ground etc.
- ***Gait quality*** - a measure of the symmetry, efficiency and effectiveness of the gait
- ***Gait symmetry*** - the amount of variation in gait parameters (e.g. step length, step frequency etc) between the right and left sides of the body.
- ***Gait training*** - rehabilitation to relearn to walk safely and efficiently
- ***Immersion*** - when the awareness of the physical world is diminished by a feeling of being inside the virtual environment.
- ***Numeric rating scale*** – A scale consisting of a range of numbers (usually 0-10 or 0-100) from which the patient selects the number which best represents their pain, with 0 representing ”no pain” and the upper number representing “ the worst pain I have ever experienced”.
- ***Optic flow*** - the pattern of apparent motion of objects, surfaces, and edges in a visual scene caused by the relative motion between an observer (an eye or a camera) and the scene.
- ***Overground walking*** - unconstrained walking on solid ground which can be either indoor or outdoor. The term is generally used when comparing this type of walking to treadmill walking.
- ***Pain affect*** - the emotional compnent of pain
- ***Pain intensity*** - the strength of the pain stimulus
- ***Psychomotor slowing*** - A slowing down of thought and a reduction of physical movements in an individual

- ***Redirected walking*** - the camera movement through the virtual environment is decoupled from the user's tracked real movements. This leads to a redirection of the actual walked path from the corresponding virtual walking trajectory, allowing virtual environments of greater extents than the operative area of the tracking system to be explored by walking
- ***Staircase method*** - A common experimental approach to identify perceptual thresholds in psychophysical evaluation. Adjustments are made from above and below the perceptual boundary until the perceptual threshold is identified.
- ***Step length*** - the distance between the two feet when walking. Measured from first point of contact of one foot to the first point of contact of the other foot.
- ***Step frequency*** – *see cadence*
- ***Vection*** - the sensation of movement of the body in space produced by a visual stimulus
- ***Visual gain*** - the ratio between the presented rate of optic flow and the current speed of self motion (e.g. presented optic flow of 3.0 m/s when walking at a speed of 2 m/s gives a visual gain of 1.5)
- ***Visual subtraction*** - sensory prediction that can be used to filter or cancel the sensory consequences of movement. When walking at a known speed, the anticipated optic flow is 'subtracted' from the presented optic flow, so that in a normal walking environment the surroundings appear stationary
- ***VE (Virtual Environment)*** – three dimensional data set describing an environment based on real-world or abstract objects and data (Stanney, 2002). Often used synonymously with VR, but is generally used to describe the computer generated components of the VR application, commonly the audio and visual elements.
- ***VR (Virtual Reality)*** - A medium composed of interactive computer simulations that sense the participant's position and actions, providing synthetic feedback to one or more senses, giving the feeling of being immersed or being present in the simulation (Craig, *et al*., 2009). VR can be used synonymously with VE but is generally considered to include both the VE, and any sensory input from or output to the user
- ***Walk Ratio*** - ratio of step length/cadence. Walk ratio is remarkably constant for an individual at different walking speeds under normal overground walking conditions
- ***Walking Protocol*** - a defined method or procedure for gait training or rehabilitation
- ***Walk speed*** - the rate at which an individual moves relative to the walking surface, often measured in m/s. It is a function of cadence and step length (Walk speed(m/s)=step length(m) x cadence(s-1))

APPENDIX A

ALGORITHM FROM THE PROGRAM TO USE TREADMILL INPUT TO CONTROL THE VIRTUAL CAMERA

```
while (!viewer.done()) //loop until the end of the program
       {
              viewer.frame(); // display the next frame of the display

              totalTravel +=travel*gear; // add the new osg travel to the total osg
units
              eye[1]+=  travel*gear;  //  add  the  converted  osg  step  (taken  from
treadmill movement and multiplied by gear)
              centre[1] = eye[1]+50; // keep focussing forwards
              viewer.getCamera()->setViewMatrixAsLookAt(eye,  centre,  osg::Vec3f(0.0,
0.0, 1.0));

…
…
…

              processData();
       }
…
…
…


void processData(void)
{
       ResetEvent(hEvent); // stops the thread while we read the data

       if( vtdData.size() != 0 ) // vtData is the array which holds the treadmill
data
                     {
                            timer = vtdData[vtdData.size()-1].dTime;
                            thisDistance          =          (vtdData[vtdData.size()-
1].dDistance)*(METERPERUNIT); // converts raw treadmill units to meters travelled
for our current treadmill
                            step  =  (thisDistance-prevDistance);  //  amount  travelled
in m
                            travel = step*OSGRATE; // converts the distance in m to
osg units
                            speed = step * (1/((timer-prevTime)/1000));// real speed
is step(m) * 1/ time in seconds i.e. m/s
                            prevDistance = thisDistance;
                            prevTime = timer;
                     }

       SetEvent(hEvent); // restarts the thread
}
```

APPENDIX B

ALGORITHM FROM THE PROGRAM TO DELIVER VISUAL GAIN CHANGES

```
int gearCount=0; // keeps track of gear changes
…
…
…

while (!viewer.done()) // until the end of the program
        {
                viewer.frame(); // display the next frame of the display

                totalTravel +=travel*gear; // add the new osg travel to the total osg
units
                eye[1]+=travel*gear; // add the converted osg step (taken from
treadmill movement and multiplied by gear)
                centre[1]=eye[1]+50; // keep focussing forwards
                viewer.getCamera()->setViewMatrixAsLookAt(eye, centre, osg::Vec3f(0.0,
0.0, 1.0));

                if(testType=='a')
                {
                        nextAutoGear(); // check to see if it is time to change
                }

                doUpdate();
        }
…
…
…
```

FUNCTIONS TO SET AND DELIVER CORRECT VISUAL GAIN (GEAR)

```
void nextGear(void) // generic function which calls the specific function.
{
        switch(testType)
        {
        case 'd':
                nextDemoGear();
                break;
        case 'a':
                nextAutoGear();
                break;
        case 'i':
                nextIncGear();
                break;
                break;
        }
}



void nextDemoGear(void)
```

```
{
        switch(gearCount)
        {
        case 0: // first gear change
                gear=0.2; // set this to a slow gear
                break;
        case 1: // second gear change
                gear=1.0; // set to fast gear
                break;
        case 2: // third gear change
                gear=2.0;
                break;
        case 3: // terminates demo
                finish ();
                CloseHandle(hEvent);
                exit(0);
                break;
                break;
        }
        gearCount=gearCount+1;
}
void nextAutoGear(void) // to set the non-prompted gain changes
{
        if((timeElapsed - autoTime)> 200) // if ready for next change
        {
                if(gear<3 && ascending==true)// if max value not yet reached
        {
                gear=gear + 0.02;
        }
        else
        {
                if(abs(gear-3.0)<0.0001) // if max value reached
                {
                        ascending=false;
                        gear=gear - 0.02;
                }
                else
                {
                        gear= gear - 0.02;
                        if(abs(gear-0.0)<0.0001) // if descended to end value then
terminate program
                        {
                                finish ();
                        CloseHandle(hEvent);
                        exit(0);
                        }
                }
                }
                autoTime=timeElapsed;
        }
}


void nextIncGear(void) // to set the prompted gain changes
{
        if(gear<3 && ascending==true)// if max value not yet reached
        {
                gear=gear + 0.2;
        }
```

```
        else
        {
                if(abs(gear-3.0)<0.0001) // if max value reached
                {
                        ascending=false;
                        gear=gear - 0.2;
                }
                else
                {
                        gear= gear - 0.2;
                        if(abs(gear-0.0)<0.0001) // if descended to end value then
terminate program
                        {
                                finish ();
                        CloseHandle(hEvent);
                        exit(0);
                        }
                }
        }
}
```

APPENDIX C

ALGORITHM FROM THE PROGRAM TO DELIVER AUDIO CUES AT SET TEMPO

```
HANDLE audioEvent; // to manage the sound
…
…
…
printf("Enter the cadence to 2 decimal places\n"); // baseline cadence
       cin>>frequency; // assign baseline cadence to variable
…
…
…
audioDelay=setAudioDelay(frequency); // calculate delay between cues depending on
cadence
…
…
…
/******for the thread to control the audio beat *****/
       audioEvent=CreateEvent(NULL, TRUE, TRUE, NULL);
       if(testType> 'd')// if audio required
       {
       _beginthread(doAudio, 0, 0);
       }


////// set the mulitplier on the audio to slow or fast relative to cadence depending
on test type
       if(audioGear=='s')
       {
              audioDelay=audioDelay / 0.75;
       }
       if(audioGear=='f')
       {
              audioDelay=audioDelay / 1.25;
       }
}
…
…
…
```

FUNCTIONS TO SET AND DELIVER CORRECT AUDIO TEMPO

```
double setAudioDelay (double frequency) // convert cadence to delay in ms
{
       return (1000/frequency);
}


void doAudio(void*)
{
       while(true)
              {
                     WaitForSingleObject(audioEvent, INFINITE);
                     if(recording)
                     {
```

```
                            double temp=(audioFinish - audioStart);
                            if(temp>=audioDelay) // if the delay is complete
                            {
                                   audioStart=audioFinish; // reset the timer
                                   PlaySound(_T("audio/step.wav"), NULL, SND_FILENAME
| SND_ASYNC);
                            }

                     audioFinish=GetTickCount(); // update the timer
                     }
              }
}
```

APPENDIX D

DOCUMENTS FOR OPTIC FLOW STUDY

Participant Information

Project Title: **“***Optic Flow in Simple and Complex Virtual Environments: Influencing Speed of Locomotion*
Supervisor: *Dr B. Stevens, Department of Creative Technologies, Buckingham Building, Lion Terrace, Portsmouth, Hampshire, PO1 3HE.*
Tel: *02392 846404*
Email: *Brett.Stevens@port.ac.uk*
Researcher: *Wendy Powell, Department of Creative Technologies, Buckingham Building, Lion Terrace, Portsmouth, Hampshire, PO1 3HE.*
Tel: *02392 846513*
Email: *Wendy.Powell@port.ac.uk*

You are being invited to take part in a research study. Before you decide whether to volunteer, it is important that you fully understand why the research is being done, and what it will involve for you. Please read the following information carefully, and if there are any parts you do not understand, or would like more information, please ask Brett Stevens or Wendy Powell (contact details above).

What is this project?
The project is a pilot study to investigate whether walking is affected by being in an artificial or “virtual” environment. Previous research has found that if people are looking at moving patterns on a screen while they are moving, it is more difficult for them to judge speeds. What this project is going to look at is whether we can find a similar effect using a 3-dimensional moving display.
The tests will be carried out using a self-propelled treadmill in the Virtual Reality room in the department of Creative Technologies.

How are participants chosen?
A general invitation has been extended to staff and students in the faculty of Creative Technologies. Initially we will need ten participants, who will be chosen at random from all suitable volunteers (see below). We will keep a reserve list until the end of the study, in case further participants are needed.

What if I change my mind?
Taking part in this project is entirely voluntary, and you are not obliged to participate. If you decide you would like to take part, you will be asked to keep a

copy of this information sheet and to sign a consent form. You are completely free to withdraw at any stage in the project, without giving a reason.

If I take part, what will I have to do?

You will be needed for about 1 hour. You will be asked to perform the following, with about 5 minutes rest between each part of the test.
Walking on a self-driven treadmill

- Walk at a comfortable pace for about 5 minutes to familiarise yourself with the equipment.
- Walk for five minutes in front of a blank screen.
- Walk for five minutes in front of a screen displaying a 3-D moving scene. This last test will be repeated 3 times, with small changes in the way the scene is animated.

During each test you will be asked to wear a pair of cardboard “glasses” to enable the 3-D effects to be viewed (these can be worn over ordinary spectacles).
After the tests, you will be asked to complete a questionnaire. You may need a few minutes rest before returning to your normal activities.

Are there any risks?

Since the tests involve physical activity, people who suffer from a heart condition, asthma or other medical condition which may be made worse by exercise are unable to be accepted as volunteers. In addition, the 3-D animation may produce a slight strobe-like effect, posing a small risk to anyone suffering from visually-induced epilepsy or fits. The Virtual Reality room contains strong magnets, which may cause problems for people with pacemakers, metal implants or shrapnel.
You will be unable to participate if you suffer from any of the above. If you have any condition which you are unsure would be a problem, please let us know before signing the consent form.
Although the study is not strenuous or dangerous, there are some potential side-effects from being exposed to 3-D animation. Some people experience mild nausea similar to travel-sickness, and there may be some slight disorientation following the tests. Both these effects are mild and only last a few minutes, but you will be asked not to leave until you have fully recovered.
You will be free to stop the tests at any time, and there will be a qualified first-aider on call throughout the tests.

Will my participation be confidential?

The data from each participant in the study will be identified by a code rather than a real name. Consent forms and questionnaires will be securely stored with access limited to authorised researchers.
All the data recorded in the study is required to be kept for several years after completion, but will be securely stored in a form which will not enable identification of individual participants.

What will the results be used for?
The results of the study may be published in a journal or presented at conferences. They may be used as part of a post-graduate research thesis.

Who is funding this research?
This project is part of a PhD research project funded by the Department of Creative Technologies at the University of Portsmouth.

How can I find out more?
If you have any questions, please contact Brett Stevens or Wendy Powell (details given above).
If you have any concerns about the conduct of the study, please contact Tony Kalus (Tony.Kalus@port.ac.uk)

Thank you for taking the time to read this information!

12th October 2005

Consent Form

Project Title: “*Optic Flow in Simple and Complex Virtual Environments: Influencing Speed of Locomotion*”
Supervisor: *Dr Brett Stevens, Department of Creative Technologies, Buckingham Building, Lion Terrace, Portsmouth, Hampshire, PO1 3HE.*
Tel: *02392 846404*
Email: *Brett.Stevens@port.ac.uk*
Researcher: *Wendy Powell, Department of Creative Technologies, Buckingham Building, Lion Terrace, Portsmouth, Hampshire, PO1 3HE.*
Tel: *02392 846513*
Email: *Wendy.Powell@port.ac.uk*

1. I confirm that I have read and understood the information sheet for the above project, and have been given the opportunity to ask questions about it ☐
2. I confirm that I am not suffering from epilepsy, asthma, heart disease or any other medical condition which might be affected by participating in this project. ☐
3. I confirm that I do not have a pacemaker or other device which might be affected by electromagnetic radiation, nor have any metal surgical implants or shrapnel ☐
4. I understand that I am participating on a voluntary basis and that I am free to withdraw at any time. ☐
5. I understand that I am not obliged to give any reason for such withdrawal ☐
6. I agree to participate in the above project ☐
7. I agree that the tests may be video recorded ☐

____________________	__________	__________________
Name of volunteer	**Date**	**Signature**
____________________	__________	__________________
Name of Researcher	**Date**	**Signature**

Optic Flow study procedure

Familiarise

Allow subject to familiarise with treadmill - check distances on belt, belt fit and slippage and position on treadmill. Ensure that speed changes are comfortable.

Procedure

Ensure video camera is charged, and correct trial and condition numbers are on the card behind the treadmill. Check the camera view to ensure that both the identifier and the reflective makers are visible.

When instructions have been given and participant is walking comfortably, start the optic flow video running. Start camera and stop-watch. Record for five minutes, stop camera and then stop optic flow video.

Instructions

Scene starts up static. Ask participant to walk steadily at their normal comfortable walking pace.

"When the software starts the image on-screen may move, as if you are walking down a road. Continue to walk at your comfortable walking pace for five minutes. I will tell you when the five minutes is finished. We will do this four times in total. You will have a short break between each of the four five-minute walks. If at any point you feel uncomfortable or want to stop, please stop walking and we will terminate the experimental trial.

APPENDIX E

DOCUMENTS FOR GAIN MATCH STUDY

Participant Information

Project Title: **“***Gain-Matching and the Perception of Self-Motion: The interaction between Optic Flow and Treadmill Walking”*

Researcher: *Wendy Powell, Department of Creative Technologies, Eldon Building West Wing, Winston Churchill Avenue, Portsmouth, Hampshire, PO1 2DJ*
Tel: *02392 845667*
Email: *Wendy.Powell@port.ac.uk*
Supervisor: *Dr B. Stevens, Department of Creative Technologies, Eldon Building West Wing, Winston Churchill Avenue, Portsmouth, Hampshire, PO1 2DJ*
Tel: *02392 845482*
Email: *Brett.Stevens@port.ac.uk*

You are being invited to take part in a research study. Before you decide whether to volunteer, it is important that you fully understand why the research is being done, and what it will involve for you. Please read the following information carefully, and if there are any parts you do not understand, or would like more information, please ask Brett Stevens or Wendy Powell (contact details above).

What is this project?

The project is investigating the perception of the speed of on-screen motion (the rate at which the display objects appear to move) compared to your own speed whilst walking on a treadmill. Previous research has found that the perception of on-screen speed does not necessarily match perception of walking speed. This project is trying to identify the on-screen speed which best matches walking speed. The tests will be carried out on a motorised “self-paced” treadmill in the Virtual Reality room in the department of Creative Technologies.

How are participants chosen?

A general invitation has been extended to all staff and students in the University of Portsmouth and the general public. Initially we will need twenty participants, who will be chosen at random from all suitable volunteers (see below). We will keep a reserve list until the end of the study, in case further participants are needed.

What if I change my mind?

Taking part in this project is entirely voluntary, and you are not obliged to participate. If you decide you would like to take part, you will be asked to keep a copy of this information sheet and to sign a consent form. You are completely free to withdraw at any stage in the project, without giving a reason.

If I take part, what will I have to do?

You will be needed for about an hour in total.

- Walk on the treadmill for a few minutes to familiarise yourself with the equipment and instructions
- Walk steadily on the treadmill whilst looking at a large display screen showing a walkway or corridor
- The speed you appear to move through the walkway will vary, and you will be asked to give verbal feedback in the form of ‘fast’, ‘slow’ or ‘normal’
- There are 5 trials will take around 5 minutes each with rests between. During this time you will be asked to wear a pair of cardboard “glasses” to enable the 3-D effects of the display to be viewed (these can be worn over ordinary spectacles).

After the tests you may want a few minutes rest before returning to your normal activities.

Are there any risks?

Since the tests involve gentle physical activity, people who suffer from a heart condition, asthma or other medical condition which may be made worse by light exercise are unable to be accepted as volunteers. In addition, the 3-D animation may produce a slight strobe-like effect, posing a small risk to anyone suffering from visually-induced epilepsy or fits. The Virtual Reality room contains strong magnets, which may cause problems for people with pacemakers, metal implants or shrapnel.

You will be unable to participate if you suffer from any of the above. If you have any condition which you are unsure would be a problem, please let us know before signing the consent form.

Although the study is not strenuous or dangerous, there are some potential side-effects from being exposed to 3-D animation. Some people experience mild nausea similar to travel-sickness, and there may be some slight disorientation following the tests. Both these effects are mild and only last a few minutes, but you will be asked not to leave until you have fully recovered.

You will be free to stop the tests at any time, and there will be a qualified first-aider on call throughout the tests.

Will my participation be confidential?

The data from each participant in the study will be identified by a code rather than a real name. Consent forms will be securely stored with access limited to authorised researchers.

All the data recorded in the study is required to be kept for several years after completion, but will be securely stored in a form which will not enable identification of individual participants.

What will the results be used for?
The results of the study may be published in a journal or presented at conferences. They may be used as part of a post-graduate research thesis.

Who is funding this research?
This project is part of a PhD research project funded by the Department of Creative Technologies at the University of Portsmouth.

How can I find out more?
If you have any questions, please contact Brett Stevens or Wendy Powell (details given above).
If you have any concerns about the conduct of the study, please contact Tony Kalus (Tony.Kalus@port.ac.uk)

Thank you for taking the time to read this information!

May 2009

Consent Form

Project Title: ***"Gain-Matching and the Perception of Self-Motion: The interaction between Optic Flow and Treadmill Walking"***
Researcher: *Wendy Powell, Department of Creative Technologies, Eldon Building West Wing, Winston Churchill Avenue, Portsmouth, Hampshire, PO1 2DJ*
Tel: *02392 845667* **Email:** *Wendy.Powell@port.ac.uk*
Supervisor: *Dr B. Stevens, Department of Creative Technologies, Eldon Building West Wing, Winston Churchill Avenue, Portsmouth, Hampshire, PO1 2DJ*
Tel: *02392 845482* **Email:** *Brett.Stevens@port.ac.uk*

1. I confirm that I have read and understood the information sheet for the above project, and have been given the opportunity to ask questions about it ☐
2. I confirm that I am not suffering from epilepsy, asthma, heart disease or any other medical condition which might be affected by participating in this project. ☐
3. I confirm that I do not have a pacemaker or other device which might be affected by electromagnetic radiation, nor have any metal surgical implants or shrapnel ☐
4. I understand that I am participating on a voluntary basis and that I am free to withdraw at any time. ☐
5. I understand that I am not obliged to give any reason for such withdrawal ☐
6. I agree to participate in the above project ☐
7. I agree that the tests may be video recorded ☐
8. I understand that neither I or my dependants will have any claim in law on the University of Portsmouth or its employees for any injury or misadventure, except when such injury or misadventure is caused by negligence. ☐

______________________	__________	______________________
Name of volunteer	**Date**	**Signature**
______________________	__________	______________________
Name of Researcher	**Date**	**Signature**

Gain match study Procedure

Gain match - linked to walking and geared automatically /incremental. Two each of incremental and automatic, one with corridor and one with pillars.

Familiarise

Allow subject to familiarise with treadmill - check distances on belt, belt fit and slippage and position on treadmill. Ensure that speed changes are comfortable. Use patient mode on box if any issues with faster walk speeds

Demo

Scene starts up unlinked from treadmill. When subject is comfortably walking, press '1' to link the treadmill, and the scene will start to move. (Starts at gear 1). Ask subject to give 'slow', 'normal', or 'fast' response for each gear change (will hear a sound when gear changes). *(Demo is n > s > n > f > stop)*

Incremental

Either pillars or corridor. Scene will start unlinked from treadmill. When subject is comfortably walking, press '1' to link the treadmill, and the scene will start to move. Changes in this are in response to keyboard entry. Ask subject to tell researcher the observed starting gear. Type ‘n’ fpr normal, ‘s’ for slow and ‘f’ for fast when participant responds. Each keyboard entry will trigger the next gear change. Program will automatically stop after all gear changes are complete.

"When the software starts you will see an image onscreen which doesn't change when you walk. When you are ready, I will link the treadmill to the screen and you will appear to walk into the scene. Continue to walk normally. I want you to tell me how the movement through the scene appears compared to the speed you are walking. If it seems too slow, say "slow", if it seems well matched to your walk speed, say "normal", if it seems too fast then say "fast". Each time you respond, you will hear a sound. There will be a change in speed of the scene, and I want you to tell me again how well it is matched to your walk speed. We will do this 4 times.

Auto

Either pillars or corridor. Scene will start unlinked from treadmill. When subject is comfortably walking, press '1' to link the treadmill, and the scene will start to move. Changes in this are automatic ask subject to tell researcher the observed starting gear, and then only if they notice a change. Will stop automatically after changes complete.

"When the software starts you will see an image onscreen which doesn't change when you walk. When you are ready, I will link the treadmill to the screen and you will appear to walk into the scene. Continue to walk normally. I want you to tell me how the movement through the scene appears compared to the speed you are walking. If it seems too slow, say "slow", if it seems well matched to your walk speed, say "normal", if it seems too fast then say "fast". After your first response, the scene speed may change at various times. If at any time you notice a change I want you to tell me again how well it is matched to your walk speed. Continue walking, and only speak if you notice a change. I may occasionally prompt you with a question such as "is it still slow?"

APPENDIX F

DOCUMENTS FOR AUDIO CUES STUDY

Participant Information

Project Title: *"The influence of visual and auditory cues on walking in a treadmill-mediated Virtual Environment for Locomotor Rehabilitation"*
Investigator: *Wendy Powell, Department of Creative Technologies, Eldon Building West Wing, Winston Churchill Avenue, Portsmouth, Hampshire, UK PO1 2DJ*
Email: *Wendy.Powell@port.ac.uk*
Supervisor: *Dr B. Stevens, Department of Creative Technologies, Eldon Building West Wing, Winston Churchill Avenue, Portsmouth, Hampshire, UK PO1 2DJ*
Email: *Brett.Stevens@port.ac.uk*

You are being invited to take part in a research study. Before you decide whether to volunteer, it is important that you fully understand why the research is being done, and what it will involve for you. Please read the following information carefully, and if there are any parts you do not understand, or would like more information, please ask Brett Stevens or Wendy Powell (contact details above).

What is this project?
Many people have difficulties with walking after illness or injury, and researchers are looking for new ways to help them to get better. One of the new techniques we are investigating uses a treadmill linked to scenes on a large computer screen (Virtual Reality). Because this is quite a new technique we need to understand more about the how it might change the way people walk. We are trying to find out how different sorts of sounds and images affect experience of walking in virtual reality.

How are participants chosen?
We are inviting healthy volunteers to take part in this part of our study, as we want to be able to compare the way healthy people walk in Virtual Reality to the way that people with pain or illness walk.

What if I change my mind?
Taking part in this project is entirely voluntary, and you are not obliged to participate. If you decide you would like to take part, you will be asked to keep a copy of this information sheet and to sign a consent form. You are completely free to withdraw at any stage in the project, without giving a reason.

If I take part, what will I have to do?
You will be needed for around one hour in the Virtual Reality Lab in the Eldon Building of Portsmouth University. You will be shown the Virtual Reality equipment and the treadmill, where you will be given a more detailed explanation of what you

will be asked to do, and an opportunity to try walking on the treadmill. If you are still happy to continue, we will start the tests. There are a number of different tests, and each of them will require you to walk at your preferred speed on the treadmill for about 3 minutes. You will be able to rest as much as you need between each test.

For some of the tests you will be looking at a scene on screen which will change as you walk, and for some of the other tests there will be some background sounds while you are walking. We will explain each test carefully to you before we start, and you will be free to stop at any time. You may be asked some questions about how you felt during the tests.

Are there any risks?

Since the tests involve light physical activity, people who suffer from a heart condition or other medical condition which may be made worse by exercise are unable to be accepted as volunteers.

Although the study is not strenuous or dangerous, there are some potential side-effects from being exposed to Virtual Reality. Some people experience mild nausea similar to travel-sickness, and there may be some slight disorientation following the tests. Both these effects are mild and only last a few minutes, but you will be asked not to leave until you have fully recovered.

You will be free to stop the tests at any time, and there will be a qualified first aider on call throughout the tests.

Will my participation be confidential?

The data from each participant in the study will be identified by a code rather than a real name. Consent forms and questionnaires will be securely stored with access limited to authorised researchers.

All the data recorded in the study is required to be kept for several years after completion, but will be securely stored in a form which will not enable identification of individual participants.

What will the results be used for?

The results of the study may be published in a journal or presented at conferences. They may be used as part of a post-graduate research thesis.

Who is funding this research?

This project is part of a PhD research project funded by the Department of Creative Technologies at the University of Portsmouth (UK).

How can I find out more?

If you have any questions, please contact Wendy Powell or Brett Stevens (details given above).

If you have any concerns about the conduct of the study, please contact Dr Tony Kalus (tony.kalus@port.ac.uk).

Thank you for taking the time to read this information!

Consent Form

Project Title: *"The influence of visual and auditory cues on walking in a treadmill-mediated Virtual Environment for Locomotor Rehabilitation"*
Investigator: *Wendy Powell, Department of Creative Technologies, Eldon Building West Wing, Winston Churchill Avenue, Portsmouth, Hampshire, UK PO1 2DJ*
Tel: *02392 845667*
Email: *Wendy.Powell@port.ac.uk*
Supervisor: *Dr B. Stevens, Department of Creative Technologies, Eldon Building West Wing, Winston Churchill Avenue, Portsmouth, Hampshire, UK PO1 2DJ*
Email: *Brett.Stevens@port.ac.uk*

1. I confirm that I have read and understood the information sheet for the above project, and have been given the opportunity to ask questions about it ☐
2. I confirm that I am not suffering from heart disease, epilepsy or any other medical condition which might be affected by participating in this project. ☐
3. I understand that I am participating on a voluntary basis and that I am free to withdraw at any time. ☐
4. I understand that I am not obliged to give any reason for such withdrawal ☐
5. I agree to participate in the above project ☐
6.

Name of volunteer	**Date**	**Signature**
Name of Researcher	**Date**	**Signature**

Audio study procedure

Audio Visual - linked to walk speed

8 * 3 min tests including baseline. With 2 min break btw each, this is < 1 hour.

Familiarise

Allow subject to familiarise with treadmill - check distances on belt, belt fit and slippage and position on treadmill. Ensure that speed changes are comfortable. Use patient mode on box if any issues with faster walk speeds. Add headphones and try again.

Headphone setup

Adjust headphones and switch on. Run the test audio file (wood1.wav) on a loop using right click and   choose media player classic. Ask subject to adjust sound upwards to maximum comfortable volume, then down one click.

Baseline

Scene starts up unlinked from treadmill. When subject is comfortably walking, press '1' to start recording the walk speed. The scene will not change, but will run for 3 mins then exit. Record a *minimum* of 2 * 30 second blocks of cadence during the 3 min test. Calculate and note cadence. (Add total number of steps and divide by seconds i.e. if 2 30 sec blocks and 20 and 25 steps then cadence = 45/30 = 1.5)

"When the software starts you will see an image onscreen which doesn't change when you walk. When you are ready, I will ask you to walk for 3 minutes at a comfortable speed. "

Trials * 7

Select order from list and enter cadence if it includes audio. The screen will prompt for correct input.

"When the software starts you will see an image onscreen which doesn't change when you walk. When you are ready, I will ask you to walk for 3 minutes at a comfortable speed. "You may hear sound in your headphones, or the image on screen may respond when you walk, or possibly a combination of the two. Continue to walk comfortably for 3 minutes until the scene closes"

APPENDIX G

DOCUMENTS FOR TREADMILL AND AUDIO / PAIN STUDIES

University of Portsmouth

McGill

Participant Information

Project Title: *"The influence of visual and auditory cues on walking in a treadmill-mediated Virtual Environment for Locomotor Rehabilitation"*
Investigator: *Wendy Powell, Department of Creative Technologies, Eldon Building West Wing, Winston Churchill Avenue, Portsmouth, Hampshire, UK PO1 2DJ*
Tel *+44 2392 845492*
Email: *Wendy.Powell@port.ac.uk*
Supervisor: *Dr M. Simmonds Professor & Director: School of Physical & Occupational Therapy, McGill University, 3654 Prom Sir William Osler, Montreal, Quebec, H3G 1Y5*
Tel: 514-398-4500
Email: *Maureen.simmonds@mcgill.ca*

You are being invited to take part in a research study. Before you decide whether to volunteer, it is important that you fully understand why the research is being done, and what it will involve for you. Please read the following information carefully, and if there are any parts you do not understand, or would like more information, please ask Maureen Simmonds or Wendy Powell (contact details above).

What is this project?
Many people have difficulties with walking after illness or injury, and researchers are looking for new ways to help them to get better. One of the new techniques we are investigating uses a treadmill linked to scenes on a large computer screen (Virtual Reality). Because this is quite a new technique we need to understand more about the how it might change the way people walk. We are trying to find out how different sorts of sounds and images affect the way you walk in virtual reality.

How are participants chosen?
We are inviting some people to take part because they have pain when they walk, and we are also inviting some people who can walk without pain so that we can see whether pain changes the way that people experience the Virtual Reality.

What if I change my mind?
Taking part in this project is entirely voluntary, and you are not obliged to participate. If you decide you would like to take part, you will be asked to keep a copy of this information sheet and to sign a consent form. You are completely free to withdraw at any stage in the project, without giving a reason. Any treatment you

may be receiving will not change, regardless of whether you decide to participate or not.

If I take part, what will I have to do?

You will be needed to attend the Jewish Rehabilitation Hospital Research Centre for about 2 hours.

First you will be asked a few questions about your general health and have some simple mobility test, and then you will be shown the Virtual Reality equipment and the treadmill, where you will be given a more detailed explanation of what you will be asked to do, and an opportunity to try walking on the treadmill. If you are still happy to continue, then we will start the tests. There are a number of different tests, and each of them will require you to walk at your preferred speed on the treadmill for about 3 minutes. You will be able to rest as much as you need between each test.

For some of the tests you will be looking at a scene on screen which will change as you walk, and for some of the other tests there will be some background sounds while you are walking. We will explain each test carefully to you before we start, and you will be free to stop at any time.

Afterwards, you will answer some questions about how you felt during the tests.

Are there any risks?

Since the tests involve physical activity, people who suffer from a heart condition, or other medical condition which may be made worse by exercise are unable to be accepted as volunteers.

Although the study is not strenuous or dangerous, there are some potential side-effects from being exposed to Virtual Reality. Some people experience mild nausea similar to travel-sickness, and there may be some slight disorientation following the tests. Both these effects are mild and only last a few minutes, but you will be asked not to leave until you have fully recovered.

You will be free to stop the tests at any time, and there will be a qualified medical staff on call throughout the tests.

Will my participation be confidential?

The data from each participant in the study will be identified by a code rather than a real name. Consent forms and questionnaires will be securely stored with access limited to authorised researchers.

All the data recorded in the study is required to be kept for several years after completion, but will be securely stored in a form which will not enable identification of individual participants.

What will the results be used for?

The results of the study may be published in a journal or presented at conferences. They may be used as part of a post-graduate research thesis.

Who is funding this research?

This project is part of a PhD research project funded by the Department of Creative Technologies at the University of Portsmouth (UK) and McGill University (Montreal).

How can I find out more?
If you have any questions, please contact Maureen Simmonds or Wendy Powell (details given above).
If you have any concerns about the conduct of the study, please contact Anik Nolet, Comité d'éthique de la recherche des établissements du CRIR
Tel: (514) 527 4527 (2643)

Thank you for taking the time to read this information.

December 2008

Consent Form

Project Title: *"The influence of visual and auditory cues on walking in a treadmill-mediated Virtual Environment for Locomotor Rehabilitation"*
Investigator: *Wendy Powell, Department of Creative Technologies, Eldon Building West Wing, Winston Churchill Avenue, Portsmouth, Hampshire, UK PO1 2DJ*
Tel: *02392 845492*
Email: *Wendy.Powell@port.ac.uk*
Supervisor: *Dr M. Simmonds Professor & Director: School of Physical & Occupational Therapy, McGill University, 3654 Prom Sir William Osler, Montreal, Quebec, H3G 1Y5*
Tel: 514-398-4500
Email: *Maureen.simmonds@mcgill.ca*

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5. I agree to participate in the above project ☐

______________________	______________	______________________
Name of volunteer	**Date**	**Signature**
______________________	______________	______________________
Name of Researcher	**Date**	**Signature**

Visual and Audio Cues project –Patient Measures and procedure

We should already have the demographic data for the patient, and also the allocation to the pain (group1) or non pain (group 2) information. From this point on, all the data you record should use the subject code, *not the name or initials*.
The data to be recorded in the patient's electronic file can be written on hard copy at this point and added later, or input at the same time, but we will **need hard and electronic copy of this data** for every patient.

- The two NRS pain scores and the SF-36 should be administered before starting, and the scores **recorded**.

- Measure the total distance walked in 6 minutes using the survey wheel and a stopwatch. During this time an assistant should count the number of steps taken to walk the marked 10m section (make a note of the number each time they walk this section, then take an average).

  You can process this data using the provided excel spreadsheet, but this does not need to be done immediately, as we will be using the TREADMILL baseline speeds for the tests.

- *Familiarise the subject with the treadmill, allowing them as much time as necessary to adapt to walking comfortably. After a rest, run the BASELINE 3 minute Caren file. It is important that this should have no visual or audio. If this is not the case, please check with Christian before continuing. Make sure that the file is reset before starting, and that the subject code is correctly entered, and then allow the subject to walk for a short time before pressing "start". During the 3 minute walk you will need to record the step frequency. This should be done across the 3 30 second blocks. This will involve using a watch with a second hand or a stopwatch, and counting (silently!) the number of steps the subject takes in each 30 seconds. The total number can be divided by 90 to give us the step frequency for the tests. At the end of this 3 minute walk (the software will automatically stop but you may need to tell the subject to stop walking), allow the subject to take a break. Open the test data file and read the bottom of the 6th column (channel 5). This will give you the distance walked in metres in the 3 minutes. Divide the last number of this column by 180 to get the walk speed in m/s. You should now have a step frequency and a walk speed. Use this data for the rest of the protocol.*

- Ensure that the headphones are connected and the cable from headphones to subject allows sufficient slack but is not a hazard.
- Check the headphones before the test to ensure that the audio is working correctly
- Connect potentiometer to subject
- When all is ready and patient is happy, press start on the Caren runtime console

Instruct patient to walk at a comfortable speed for 3 minutes until the test stops automatically (sound or visuals or both will stop), and then to stop walking and rest. Let them know when each minute is complete, but discourage dialogue. Tell them to stop walking and rest when the visual or audio stops.

- Repeat the above step for each trial, making sure you have done the **stop/rewind** on the Caren, and the **new trial / capture** on the Vicon before continuing. The correct ‘next trial’ will automatically be selected.

- For the pain group, the two NRS pain scores should be administered again, and the scores **recorded**.