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# BuzzwireVR: An Immersive Game to Supplement Fine-Motor Movement Therapy

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## Abstract

*Recovery of upper-body fine-motor skills after brain trauma, e.g. after a stroke, involves a long process of movement rehabilitation. When the arms and hands are affected patients often spend many hours exercising in order to regain control of their movements, often using children's toys. This paper describes the process of development of a Virtual Reality (VR) system designed to supplement rehabilitation by encouraging hand movements while playing a fun game. The system is based on the well-known Buzzwire children's toy that requires steady hand-eye coordination to pass a ring along a wire without touching the wire. The toy has in the past been used in a variety of research studies, but we considered it ideal for motor rehabilitation because it requires steady hand and finger movements. In our virtualised version of the toy the wire consists of a parametric spline curve with cylindrical cross-section positioned in front of the player. Cylinders at the ends of the 'wire' change colour to indicate which hand to use. The parametric nature of the wire allows us to record performance variables which are not readily available in the physical version. We report on two initial experiments which tested and evaluated various aspects of performance on able-bodied participants and stroke patients, followed by a description of how we developed the toy into a multi-level game that encourages increasingly intricate hand movements. In the first evaluation we tested if performance variables (such as average speed, and distance from the wire) could distinguish between dominant and non-dominant hands of able-bodied participants. We also compared performance with and without binocular viewing. Results showed that our metrics could distinguish between the players dominant versus non-dominant hand. We also noted a dramatic disruption of performance when binocular stereopsis was not available. The second experiment was a usability study involving a sample of stroke-affected participants with post-stroke hemiparesis. Results showed positive acceptance of the technology with no fatigue or nausea. Our gamified version of the task utilizes learnings from the previous studies to create an enjoyable multi-level game involving auditory guidance as feedback. Results are discussed in terms of potential benefits of using such technology in addition to conventional therapy.*

## CCS Concepts

• **Computing methodologies** → **Virtual reality**; **Perception**; • **Human-centered computing** → **Virtual reality**;

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## 1. Introduction

From infancy, we learn through activity. With little control over our limbs, learning about the world begins through a process of exploration by touching, looking, smelling, and tasting the world around us. Like the sensory system, the human motor system is hierarchical in nature and is guided by sensory (especially somatosensory) feedback. Motor system coordination improves with practice and learning. There are many different types of motor skills and actions. For example, ballistic movements like swatting a fly are fast, brief and well-practiced and do not require sensory feedback. Such reactive movements are unconscious, relying mainly on proprioceptive feedback. Skilled motor tasks (e.g. writing, riding a bicycle, playing

tennis), on the other hand, require coordination between the perceptual and motor systems. The initial phases of learning here require conscious control of individual movements of the limbs. Lack of fluidity in motion is a characteristic of the 'player' having to consciously control their movements based on the task, visual inputs and motor control. After learning, control of individual movements becomes integrated into a string of movements adjusted by unconscious sensory control. As Luria [Lur12] put it, these sequences of motions form a 'motion melody' resulting in faster, more efficient motor responses requiring less energy and less conscious control.

After trauma to the motor areas of the brain (e.g. the posterior parietal areas, and primary and secondary motor cortices), even simple tasks requiring sensorimotor control have to be relearned. For example, a lengthy period of rehabilitation is always required after a person suffers a non-fatal stroke. Many hours of therapy are nec-

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essary whereby rehabilitation experts use basic exercises such as stacking objects, finger painting and playing with children's toys. Although the latter provide a form of exercise for patients, they do not allow for the precise measurement of movements and therefore of the degree of improvement in manual dexterity. Video-taping and analysis of temporal assessment of dexterity are limited in their scope for analysis of systematic errors in movement. Furthermore, adherence to rehabilitation programs is low. Factors including fatigue, poor health, lack of motivation, and musculoskeletal issues may prevent people with stroke from initiating or maintaining therapy programs [JMO11].

We believe that immersive and augmented reality technologies for the display and tracking of movements can be utilized beneficially as a supplement to the rehabilitation of body and limb movements after damage to the motor areas of the brain. The combination of computer-generated environments, which can produce limitless scenarios, and hand and body tracking provide an ideal methodology for quantifying changes in sensorimotor integration and tactile (hand-eye) coordination. Initial reviews by neurologists [HKBL07] suggests that virtual reality (VR) is a potentially useful technology for upper limb motor rehabilitation (for further reviews see [CBV08] and [LLG\*17]). Others have considered the potential benefits of VR in the promotion of neuroplasticity, the regeneration of neural connectivity that allows patients to regain manual dexterity [CTAB14]. The general consensus appears to be that since continuous practice of movements after stroke or other motor area damage is beneficial for recovery, then any therapy, including VR therapy, will also be beneficial.

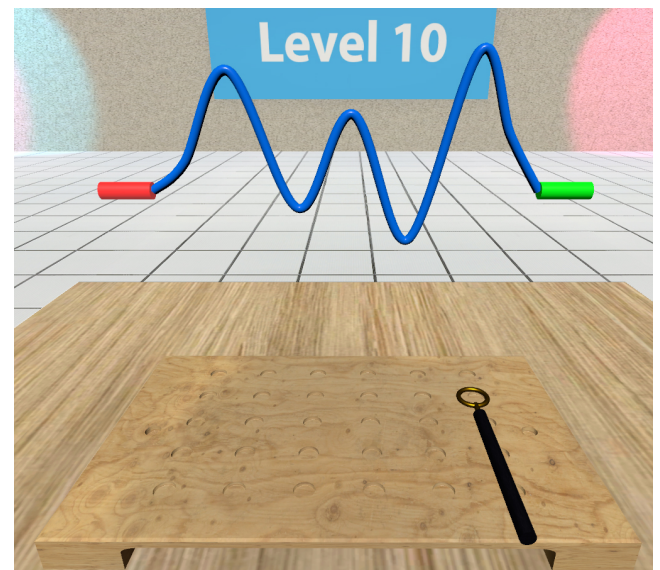
In this paper we report on the process of developing one of several planned games designed to supplement conventional clinic-based physiotherapy. The VR system we chose to develop first (see Figure 1) is best suited for fine-motor hand and finger control and is based on the well-known children's toy called the loop and wire test, or Buzzwire. Physical versions of the Buzzwire toy involve moving a ring across an undulating wire, testing one's hand-eye coordination. If the ring makes contact with the wire an electrical circuit is closed and a buzzing noise is heard. The toy has been used in a number of empirical studies. For example, [DJML12] used it as one of a number of tools in the study of obsessive-compulsive disorder whereas [CMK\*14] used it to study autism in children. Ref. [SLE\*16] used it in a study concerning comfort and ergonomics in the workplace. More relevant to our work [BLH\*14] used it to evaluate the effect of a short-term dexterity-training on muscle tremor and the performance of hand precision tasks in patients with essential tremor. Ref. [RBMT13] used it to study binocular advantage in fine-motor skills with tools.

Here we report on a series of experiments that led to the creation of a gamified version of the toy implemented in a local movement rehabilitation clinic. Our first experiment involved able-bodied participants and tested whether our experimental measures were powerful enough to distinguish performance between participants dominant versus non-dominant hands. We considered that being able to make this distinction based on our measurements to be essential if we are to be able to determine improvements in a final version of the application being used by movement-impaired participants. It is also relevant to our application as some research suggests that

hand dominance is a neurological phenomenon (e.g. [Hol01]) and future studies may find it useful as a way of correlating neurological changes with changes in handedness related dexterity.

The first experiment also tested the importance of stereo vision in performing the task. Stereopsis provides depth information and can be used to guide a person's hand towards an object in space. Previous research using the physical Buzzwire toy suggested that the provision of stereopsis is important (e.g. [RBMT13]). However, depth cues are also available from other visual cues such as motion parallax. Furthermore, immersive environments are usually facilitated by Head Mounted Displays (HMDs) which require adjustment of their optical system to match the interocular separation of the user for optimal stereopsis. It was therefore important for us to see if stereo vision is an important cue for this immersive scenario. If it is, then more care must be taken in the adjustment of the interocular distance of the device being used.

Our second experiment was a usability study involving a small number of stroke affected patients attending a local rehabilitation clinic. It tested whether the VR equipment was appropriate for such a task and whether the experience was found rewarding and enjoyable by the participants. Finally, we describe the features of the full multi-level game developed in accordance with learnings from the prior two experiments and report on some of the initial data collected after several participants played the game for a few weeks.



**Figure 1:** The 'buzzwire' curve floats above a peg-board in a simple room with a table. The starting direction is indicated by the green cylinder. The rod and ring (right) is used to traverse the wire. A sign at the back of the room indicated the current level to the player.

## 2. General Description of the VR Application

### 2.1. Hardware

The VR display used was a HTC Vive HMD with a resolution of 1080x1200 pixels per eye and 110 field of view. Each of the two screens of the HMD had a refresh rate of 90Hz. User input was achieved with a single hand-held controller (Figure 2), a virtual depiction of which was also visible in the environment. The position and orientation of the display and the controller were tracked within a space of 2 square meters, although the participants were seated during the tests. The head and controller tracking were based on a lighthouse system with lighthouses placed at opposite ends of the tracking area and approximately 3 meters apart.



**Figure 2:** The HMD shown with the wand that is used to control the virtual ring and rod.

The virtual ring and wand were controlled by an additional HTC Vive Tracker attached to a rod (see Figure 2). The Vive Tracker is a 10cm wireless tracking accessory that has a universal mount at the bottom. A positional tracking accuracy of around 2mm has been reported for this system (<http://doc-ok.org/?p=1478>). Initial tests with this tracker revealed no perceptible lag between movements of the hand and display update. When participants ‘touched’ the wire sparks could be seen at the point of contact. An audible spark sound was also heard. The sound was kept low, so as not to disturb participant’s movements, but still inform them of collisions. The sound was 12 dB higher than the background sound level (average 43 dB). The ring could pass through the wire without rigid body physics effects on either: that is, the wire and ring of the wand could pass through each other. There was no actual haptic feedback when one touched the other and the ring could pass through the wire.

The virtual environment was rendered by a Windows 7 workstation with Intel Core i5-4690K 3.5GHz CPU & 8GB RAM with NVidia GeForce GTX 970 GPU with 8GB on-board memory.

### 2.2. Simulation Software

The Unity3D game engine was used to create the game design with lighting, particle systems (sparks on collision with the wire),

and immersive environment. The SteamVR SDK was used to handle display of the scene, the tracking data from the sensors, and user interaction from the hand-held HTC Vive tracker. Custom C# scripts controlled the flow of the experiment: the presentation of each trial including generation and presentation of wires, randomization and presentation of trials and data collection and storage. After each trial, performance averages (time, deviations, number of collisions, average speed, see below) and position and orientation of the wand’s ring center were stored for offline analysis. The ‘wires’ were formed using meshed spline curves.

### 2.3. Meshed Spline Curve Generation

The wires used in the experiment were generated using cubic Hermite interpolation, initially across 12 control points although this was changed in the final game. The control points could either be generated dynamically by varying their position, or within the Unity3D editor. For the first two experiments their position was fixed and adjusted by hand within the Unity3D editor to form 5 unique wires which made it possible to compare player performance. Our final version of the game utilized randomly generated curves (see below). The interpolation polynomial between two control points can be written as in Equation 1:

$$\mathbf{p}(t) = h_{00}(t)\mathbf{p}_0 + h_{10}(t)\mathbf{m}_0 + h_{01}(t)\mathbf{p}_1 + h_{11}(t)\mathbf{m}_1 \quad (1)$$

Where  $h_{00}$ ,  $h_{10}$ ,  $h_{01}$  and  $h_{11}$  are Hermite basis functions. The set of control points ( $\mathbf{p}$ ) was interpolated by applying the above procedure on each interval with the tangents ( $\mathbf{m}$ ) between each interval being equal producing a piecewise smoothly differentiable line. Because of their parametric nature, the total length of the resulting curves could be calculated and used to accurately record mean speed, and shortest distance from the wand ring center to each curve.

The spline curves were converted to mesh objects by generating cylindrical segments at fixed intervals along the entire curve. The interval chosen produced smooth curves whilst limiting the overall number of polygons required. The diameter of the wire mesh was equivalent to 1cm.

## 3. Experiment 1

This experiment tested the importance of two independent variables; handedness and stereopsis. Several measures of accuracy/efficiency were used including the traditional count of number of collisions made with the wire but also other measures which are not available in physical versions of the game (see below).

### 3.1. Handedness

Handedness means better performance, or individual preference, for the use of one hand (referred to as the dominant hand) over another (referred to as the non-dominant hand). The non-dominant hand is less capable or less preferred than the dominant hand. Questionnaires exist to assess a person’s preference for one hand over another [Old71]. Right-handed people are more common. Our background research found no study using the Buzzwire toy to assess a dominant over non-dominant hand preference. In stroke patients with hemiparesis, where the dominant hand is debilitated,

they must either learn to use their non-dominant hand as their dominant hand or regain their original abilities in their dominant hand. In this case their recovery is more challenging as certain important capabilities, such as their ability to write for example, are impaired.

### 3.2. Stereopsis

The buzzwire toy has in the past been used to study the influence of stereopsis on fine-motor dexterity in adults [MMG91]. They measured the number of contacts between a loop and wire as a function of the stereo acuity of 4 groups of people of varying stereo acuity. They found that performance was severely reduced for the no-stereopsis group as compared to the group with normal stereo acuity. There was, however, no linear correlation between stereo acuity and performance. Ref. [JDB01] found that the task took longer to complete with monocular vision. Similarly, [RBMT13] looked at the importance of binocular viewing in three common manual dexterity tasks (Morrisby Fine Dexterity Test performed with fingers and with forceps and the Buzzwire task) and found that only in the Buzzwire task did stereopsis make a significant contribution to performance. They argued that tasks performed with the use of tools would place more emphasis on visual (stereopsis) inputs than prehension tasks in which proprioceptive information is available from the fingers.

### 3.3. Design

All of the previous experiments utilizing Buzzwire to assess fine motor skills have used the number of contacts made with the physical wire as their dependent variable. Some also timed the task to completion. We believe that these measures are rudimentary and much of the useful data of the task is lost when analogue procedures are used. By using a virtual version of the task, we can track the user's hand with precision and identify systematic errors. Furthermore, we are able to calculate more performance measures such as average speed, maximum velocities and acceleration.

A within-subjects design was used to assess players ability to manoeuvre over 5 curved wires keeping the wire in the center of the ring. We compared players dominant versus non-dominant hand control across the same wire by having them traverse each wire with both their dominant and non-dominant hand. Presentation of each wire was randomized. In the first part of the test participants performed the test with binocular vision. In the second part the screen for their non-dominant eye was turned off producing a monocular display. The same set of wires (in randomized order) was used for both binocular and monocular tests. The following experimental variables were measured:

- The time taken to complete each wire. Timing began as soon as the ring passed an invisible collision detector at the beginning of the wire and stopped in a similar fashion at the end of the wire.
- The number of collisions made between the ring and the wire.
- The mean deviation from the exact center of the ring and the spline representing the wire.
- The total distance traversed by the ring from beginning to end of trial. This would match the wire length exactly if no deviations were made.
- The average speed from beginning to end of each wire.

Participants were informed which hand to use by changing the colour of the start position to green (see Figure 1). Thus, if the start cylinder was green on the right side, they used their right hand to perform the task. Their dominant hand was recorded by the software and this allowed us to record data in terms of dominant versus non-dominant hand.

### 3.4. Participants

Eighteen able-bodied volunteers participated in the experiment (9F,9M). Mean age was 33.2 (Median 34), 70% had played with the real toy before. Each subject completed the Edinburgh Handedness Questionnaire prior to the experiment to determine their dominant hand. Mean extended test score was +74.5 (median 88.5). Only one left-handed person was amongst our sample. Their dominant eye was also determined (using the hole-in-card test). An informal stereo test with the Randot Stereotest (<https://www.stereooptical.com/>) ascertained a minimum level of stereopsis set at 200 arcsec.

### 3.5. Results

Results for our main measure, deviation from the wire, showed that the best performance was with stereo vision using the dominant hand (mean deviation=0.4cm, s.e.=0.02cm). The fastest time was similarly with stereo vision and participant's dominant hand (mean=18.4sec, s.e.= 1.35). This pattern was observed for all our other measures demonstrating that the most effective way to play the game was with stereo vision using the dominant hand. Separate within-subjects repeated-measures analysis of variance (ANOVA) were performed on the individual scores for time taken, number of collisions with the wire, average deviation of the center of the wand loop to the spline curve, total distance covered in traversing the wire and average speed. There were three main factors STEREO (2 levels, Binocular and Monocular), HAND (2 levels, Dominant and Non-Dominant and WIRE (5 levels for the 5 wires). Table 1 shows the results and confirms stereo was in all measures significantly better with binocular vision than with monocular vision. Furthermore, it shows that with the dominant hand the total time taken, average deviation and average speed were significantly better with the dominant hand.

**Table 1:** Shows the results of an analysis of variance on the data in Experiment 1.

Measure	STEREO		HAND		WIRE	
	F(1,17)	p	F(1,17)	p	F(4,68)	p
Time	12.90	.002*	5.72	.028*	4.53	.017*
Collisions	73.73	.000*	2.23	0.15	0.93	.451
Deviation	41.90	.000*	5.08	.037*	3.63	.009*
Distance	12.34	.003*	0.40	.577	2.76	.034*
Speed	7.13	.016*	6.19	.025*	1.12	.353

### 3.6. Summary

Results confirmed that the provision of binocular stereopsis is important in all of the measures that we have recorded even though additional depth information was available via motion parallax. Most

significant of these measures is the deviation of the ring center from the wire that had to be followed. Such a measure was not previously used in physical versions of the game and indeed would be very difficult to implement. The use of the dominant hand was also found to produce better results. This was observed in terms of time taken, average deviation from the wire and total distance covered.

In summary, we have replicated the results of previous experiments which found that binocular vision is beneficial in this hand-eye coordination task (e.g. [RBMT13]). Moreover, using measures which have not previously been used (deviations from the wire and average speed) we have been able to reveal that the dominant hand of an individual produces faster and more accurate motion than the non-dominant hand. There is no reason to believe that handedness is a result of weakness in anatomical structure of the non-dominant hand therefore the bias may be neurological. Indeed, some studies have already suggested a connection between left-hemispheric language dominance in the human population and the prevalence of right-handedness in individuals [Hol01].

We therefore believe that the virtual reality version of the game could make a useful contribution to the assessment of fine motor hand-eye coordination as long as there is stereo vision provided to the player. We next proceeded to test the fine motor skills of several patients with known motor skill deficits so see if such methods are at least feasible in terms of usage and whether they could potentially be used as an entertaining form of motor skill exercise with the added ability to measure progress and improvement over time.

#### 4. Experiment 2

The second experiment took place at a local rehabilitation clinic and involved the same task with the same design except that participants were not required to perform the test using monocular vision as we have established that binocular viewing is required for good performance.

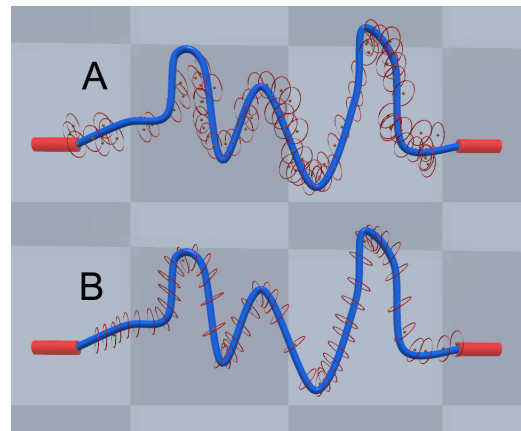
##### 4.1. Participants

Eleven chronic-stage outpatients with varying degrees of upper body hemiparesis took part in the experiment. Nine patients had right-side hemiparesis or hemiplegia after stroke (6 ischemic, 3 hemorrhagic) and two left-side hemiparesis (one ischemic, and one hemorrhagic). Patients had at least a reasonable ability to make horizontal hand movements with both hands and had suffered a stroke more than 6 months prior to the test and within the last 2 years. Their mean age was 55.5 years (median 48). Participants were either seated in a chair or wheel-chair depending on the level of their disability. Handedness prior to injury was not considered and stereopsis was assessed as in the previous experiment. Our data was recorded in terms of subjects' weak and strong hands.

##### 4.2. Procedure

Participants first signed a consent form, had their stereo vision assessed and were shown a video describing the experiment. They then proceeded with the test. Some patients needed help with gripping the wand correctly and adjusting the initial position of their hand, depending on the amount of weakness they experienced.

They performed 5 trials independently with their weak hand and 5 trials with their stronger hand (the order, left and right, was randomly interspersed).



**Figure 3:** Visualisation of movements during a trial by a patient with left-side hemiparesis. (A) Left hand. (B) Right hand.

#### 4.3. Results

We noticed most of the difficulties in accurately following the wire arose from lack of rotation (pronation and supination) in arm and hand movements. This could be easily seen in visualizations of the participant movements that were recorded during the experiment (see Figure 3). These show an inability to rotate the wand so that the ring was centered around the wire as it changed curvature. Translational movements (right to left, left to right) were slow and staggered, but nevertheless participants managed to traverse the distances from start to end points with hemiparetic and unaffected hands.

We also noticed that some participants were so poor at following the wire that they used the sound of collisions as a guide. The reason for their inaccuracy was either a result of poor visual acuity or poor motoric ability. Regardless, this gave us an insight into how to improve the game for future versions; namely, to provide auditory feedback not just when users collided with the wire but also when they were doing well and following the path with accuracy. Such feedback could, for example, be provided by modulating the volume of some feedback sound depending on how close the ring center is to the wire. Table 2 shows mean results for each dependent variable.

**Table 2:** Shows the results of an analysis of variance comparing the hemiparetic (weak) and stronger hand in Experiment 2.

Measure	HAND (means)		ANOVA	
	WEAK	STRONG	F(1,10)	p
Total Time (s)	33.7	26.5	8.13	.002*
Collisions	18.3	9.0	24.3	.000*
Deviation (m)	0.02	0.01	5.18	.046*
Total Distance (m)	1.73	1.0	10.4	.009*
Speed (m/s)	0.06	0.04	5.32	.044*

dent variable. To determine the significance of these results we performed separate within-subjects ANOVAs on the data as in the previous experiment although this time the main factor was Hand only (2 levels, weak or strong, corresponding to patient’s hemiparetic and unaffected hand). This analysis showed significantly worse performance in all dependent measures when using the stroke affected hand. We also observed much worse performance than in our previous experiment although a fair comparison is not possible considering the very small samples size and the large differences in age between participants.

In this experiment we also asked patients a number of questions after the test to assess any difficulties with the apparatus and feelings of discomfort. The questions were assessed using a 5-point Likert scale ranging from 1=Total Disagreement to 5=Complete Agreement. Table 3 shows median and interquartile range scores for each question. Results reflect a positive acceptance of the technology.

**Table 3:** Results of usability questionnaire with median and interquartile range (n=11).

Question	Median	IQR
I felt general discomfort during the test	1	0
I felt fatigue wearing the device	1	0
I felt my eyes strained	1	0.5
I had difficulty focusing on the scene	1	1
I enjoyed the experience	5	0
I felt nausea during the test	1	0

#### 4.4. Summary

The results reflected the weakness of the stroke-affected hand. This difference is not surprising in terms of performance but our subjective (questionnaire-based) analysis showed generally that wearing the HMD did not produce much discomfort and there were no reports of nausea (often associated with large movements in virtual environments). Some patients did however report difficulty in focusing on the scene, possibly because of difficulty in adjusting the distance of the HMD lenses from the eyes to an ideal position for each observer. There may also be an issue in accurately adjusting the interocular separation of the HMD screens.

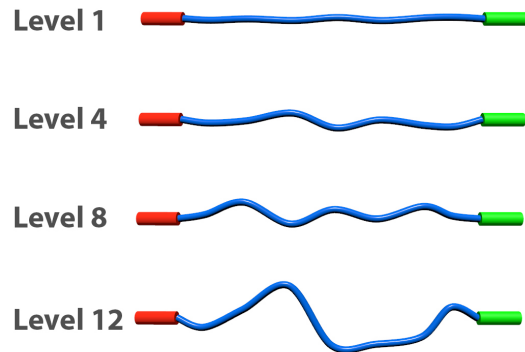
Observations of these patients showed they had difficulty in traversing the curved wires accurately with their weakened hand, mainly owing to an inability to rotate their hands easily. Patients were helped initially to position their limbs and here we noticed a requirement for the experimenter to be able to see the same scene as the patient in the virtual environment. Possibilities here might include the use of shared virtual environments where both patient and therapist can initially observe the same scene.

#### 5. Prototype Game Version

Based on our previous findings we wanted to create a multi-level version of the buzzwire game that encourages its players to

progress from an easy level to an increasingly greater level of difficulty. Having multiple levels of difficulty enables even those with severe weakness to exercise whilst encouraging a sense of achievement. In this case it is necessary to consider why people find this game challenging in general, but also why stroke-affected players would find it especially challenging. Our second experiment involving stroke-affected players revealed two main forms of difficulty in traversing the wires: Firstly, through observations, we noticed an inability to keep a steady hand owing to dyskinesia. Secondly, visualisations of movements (see Figure 3) reveals a lack of forearm pronation and supination. The latter suggested that one way to vary the level of difficulty was to vary the number of bends in the wires and this in turn is determined by the number of control points along the spline curve. However, varying the number of control points after a certain degree can produce odd shapes in the wires. We therefore decided to vary the level of difficulty by varying the *height* of a fixed number of control points. This also has the added advantage of exercising both horizontal and vertical arm and hand movements.

The prototype game that has been developed involves multiple levels whereby subsequent levels increase the maximum allowable vertical position of the control points. As in the previous studies these control points remain in the same depth plane, however in future developments this can form another increment to the level of difficulty. Thus, at the easiest level, the control points were restricted to a maximum of around  $\pm 1cm$  deviation from the horizontal producing shallow bumps along the wire. The movements of the player in this case are mainly lateral. The maximum height was increased linearly from level to level so that at level 12, for example, the control points could deviate by as much as  $\pm 12cm$  from the horizontal (see Figure 4) encouraging greater vertical movements and more rotations of the hand.



**Figure 4:** Shows screen captures of the wires from different levels of the game. The curves’ height is not representative as this depends on the display device.

The spline curves were generated using 9 control points at fixed horizontal intervals and randomly chosen vertical positions. The first and last control points were constant. To reduce the possibility

**Table 4:** Shows the progress of some of our participants playing the game over several days.

Patient	Number of Sessions	Total Games Played	Highest Level Attained
1	2	4	2
2	2	12	12
3	3	12	12
4	4	22	10
5	1	4	0

of steep transitions at the extremities of the wires the randomly generated control points were weighted according to a Gaussian profile. A further change to the previous versions is a reduction in the overall horizontal length of the wires so that players do not have to move their hands excessively in the horizontal direction.

Players are still required to play the game using both hands. This allows us to make comparisons of improvements with the hemiparetic and unaffected hands as players are expected to get more proficient as they continue playing.

Other findings from the studies reported above were incorporated into the final version. For example, we previously found that some patients had so much difficulty following the wire that they used the buzzing from collisions to guide their hand movements. This gave us the idea of providing auditory feedback when the ring encircled the wire. The audio feedback provided was a short ‘blip’ sound whose tempo was increased linearly as the loop approached collision with the wire, much like the looming auditory collision warnings found in newer automobiles.

The game is otherwise like the previous versions; however it has been fully automated with voice recorded instructions including for when players have to change hands and when they succeed at each level. Recordings of progression through the game are made in the form of session files which store the patient’s details and other game information at each sitting. We also record the metrics used in previous experiments reported above. This allows us to track changes and improvements as players play the game on different occasions.

Table 4 shows details of 5 outpatients who have so far used the system and reflects a large variability in performance. All patients have chronic-level hemiparesis and played the game in different sessions over the course of 14 days. Some of them found it apparently easy, whilst others apparently could not progress beyond lateral hand movements.

What we currently lack is an independent measure of improvement over time. The metrics used in the initial tests (e.g. total time taken, etc.) are valid for comparisons only with the same curves (wires). The current version of the game randomizes the curves continuously. We therefore require some independent metric to continually assess performance. Human upper-limb movements are never the same; in both healthy and stroke-affected populations. Researchers have previously suggested measurement of kinematic smoothness as such a measurement, e.g. [RFK\*02]. Smoothness

can be measured using several metrics including minimum jerk (the average change in acceleration during arm movements). However, for complicated upper-limb dynamics it is still a topic of debate as to how it can be quantified [BMCRBB15].

## 6. Conclusion

The studies reported here involved a virtualized version of the loop and wire toy, also known as Buzzwire, that could be played in VR. This interactive application was devised as part of a project to create VR tools for people who have movement disorders after brain trauma to exercise their weakened limbs while data is collected to assess improvements in motor control. The popularity of the original toy is derived from the fact that it requires a steady hand, intricate hand and finger movements and accurate hand-eye coordination. A virtualised version can be turned into a game whereby the level of difficulty can be adjusted automatically based on performance, but which can also store information regarding performance. Our initial studies therefore involved an assessment of various types of information that can be collected from playing the game in a virtual environment.

In the first experiment we showed that the VR version of the game may provide data that is not easily obtainable using the physical version of the game. We were able to measure the accuracy with which players could traverse the wires keeping the wire in the center of the ring. We were also able to measure average speed with which they traversed the wire. Both measures have not been used in physical implementations of the game as used for fine-motor skill studies. This data was used to demonstrate that, as in the physical version of the game, stereopsis is highly desirable if not essential for accurate hand-eye coordination. Furthermore, we were also able to demonstrate an effect of handedness (dominant versus non-dominant hand) in playing the game.

In the second experiment we tested the feasibility of this type of VR application for motor rehabilitation on a group of participants who had suffered stroke. Head-mounted displays, although improving continuously, are still relatively heavy and immersive. This could potentially cause fatigue and other difficulties such as nausea. In terms of comfort and ease of use we were surprised by how easily patients adapted to the technology. We used the same measures in patient’s ability to play the game as in Experiment One. We were able to show differences between patient’s hemiparetic hand and unaffected hand. These results are encouraging and were used to develop a more complete prototype game with different levels to add a sense of achievement and progression. The application is still being refined and future tests may involve long-term comparisons of improvements over time. Research suggests that frequent exercise of motor control after stroke is positively correlated with recovery (e.g. [KvPW\*04]).

We conclude by considering the usefulness of this technology for rehabilitation purposes. With the adoption of any new technology we must consider two main questions: Is it equivalent, if not better, than previous methods? And, is it cost effective? To answer the first question, we have shown that using virtual methods it is possible to create a wider variety of scenarios, that the measurements which we can make are broader (e.g. in terms of deviation



accuracy and average speed), and that it is possible to store motion data in real-time for off-line analysis to access motion paths and assess systematic errors.

In relation to the second question we must consider that the recovery from brain trauma involves months and even years of sessions of therapy on a one-to-one basis with a trained therapist. This is not only a time-consuming process, but it is also very expensive. The therapist deals with one patient at a time and the patients must usually attend a clinic that is often far away from their home. This is especially difficult when the patient is bound to a wheel chair. In this respect VR technology may prove to be a cost-effective alternative to keep patients exercising while they are not attending physiotherapy clinics. With the continual reduction in costs, interactive applications such as the one described here may provide ideal supplements to motor recovery.

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