

# Quantifying cognitive-motor interference in virtual reality training after stroke: the role of interfaces

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## ABSTRACT

Globally, stroke is the second leading cause of death above the age of 60 years, with the actual number of strokes to increase because of the ageing population. Stroke results into chronic conditions, loss of independence, affecting both the families of stroke survivors but also public health systems. Virtual Reality (VR) for rehabilitation is considered a novel and effective low-cost approach to re-train motor and cognitive function through strictly defined training tasks in a safe simulated environment. However, little is known about how the choice of VR interfacing technology affects motor and cognitive performance, or what the most cost-effective rehabilitation approach for patients with different prognostics is. In this paper we assessed the effect of four different interfaces in the training of the motor and cognitive domains within a VR neurorehabilitation task. In this study we have evaluated the effect of training using 2-dimensional and 3-dimensional as well as traditional and natural user interfaces with both stroke survivors and healthy participants. Results indicate that 3-dimensional interfaces contribute towards better results in the motor domain at the cost of lower performance in the cognitive domain, suggesting the use 2-dimensional natural user interfaces as a trade-off. Our results provide useful pointers for future directions towards a cost-effective and meaningful interaction in virtual rehabilitation tasks in both motor and cognitive domains.

## 1. INTRODUCTION

Cerebrovascular accidents (CVA) or strokes are caused by disruption of the blood supply to the brain, resulting from either blockage (ischaemic stroke) or rupture of a blood vessel (haemorrhagic stroke) (MacKay and Mensah, 2004). Every year about 16 million new strokes are recorded worldwide (Strong, Mathers, and Bonita, 2007), making stroke one of the main causes of adult disability and it is expected to be one of the main contributors to the burden of disease in 2030 (WHO, 2008). Consequently, many stroke survivors suffer chronic conditions that require continuous treatment and rehabilitation, reducing their independence for basic everyday activity tasks, with a significant psychosocial and financial burden on patients, relatives and healthcare systems (Vincent et al, 2007). Therefore, with an estimated cost of 102 billion \$ annual cost in the EU and USA combined (Di Carlo, 2009), a pressing need to find solutions that can help alleviating this situation is present.

Recovery after stroke is slow, and the impact of current rehabilitation approaches mostly depends on the availability of highly trained health professionals, and access to the training frequency, intensity and duration that are needed. Unfortunately, public healthcare systems cannot always provide patients with the ideal long-term rehabilitation that is necessary. Virtual Reality (VR) for rehabilitation is an approach that provides novel solutions that can contribute towards low-cost and long-term rehabilitation (Bermudez i Badia and Cameirao, 2012) as well as support the requirements for an effective training. Through VR, researchers design fully controlled environments with specifically designed for different diagnostics and motivate patients through personalised tasks and feedback (Lucca, 2009). Besides immersive or non-immersive VR based rehabilitation systems, Serious Games have been used for training (Alankus, Lazar, May, and Kelleher, 2010; Burke et al, 2009), capitalising in motivational factors that are essential for recovery (Maclean, Pound, Wolfe, and Rudd, 2000). In addition, these novel approaches to rehabilitation not only allow for the individualization of training and monitoring by physicians, but also enable patients to play a more active role in their rehabilitation process by

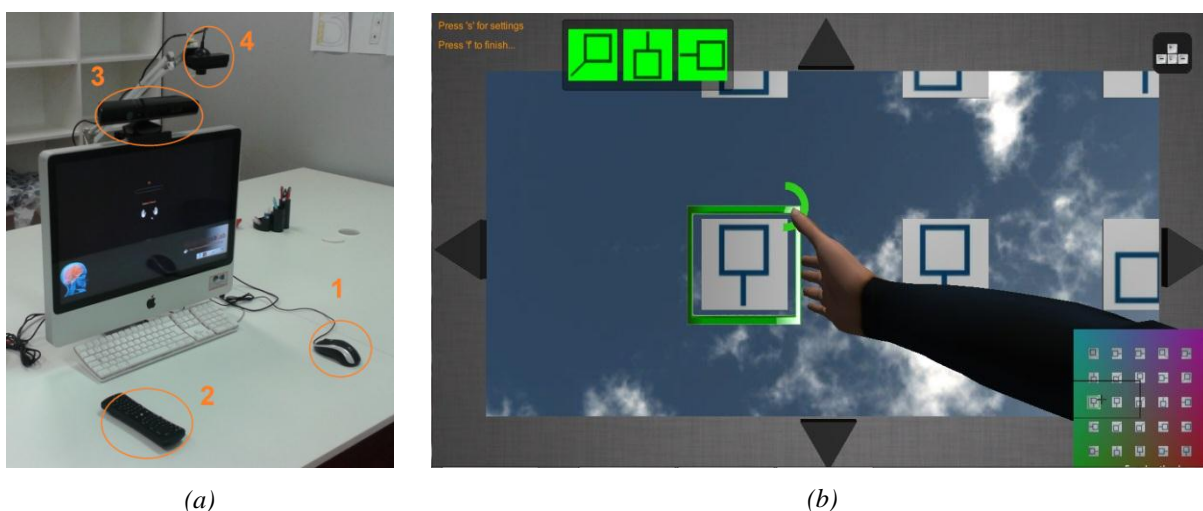
self-monitoring their own improvements in their private space. In fact, VR training for stroke survivors has been assessed in the past with encouraging results (Broeren, Rydmark, Björkdahl, and Sunnerhagen, 2007; Cameirão, Badia, Duarte, Frisoli, and Verschure, 2012). Further, a recent Cochrane review included 19 of the latest studies with a total of 565 participants for comparing the impact of VR (Laver, George, Thomas, Deutsch, and Crotty, 2012). Through this meta-analysis can be found that VR is more effective in the retraining of activities for daily living (ADL) compared to traditional methods. Unfortunately, accessibility to these therapies remains a challenge especially for patients with severe disability and worse predicted outcome.

In order to tackle the accessibility limitation of VR systems, approaches such as the RehabNet (Vourvopoulos, Faria, Cameirao, and Bermudez i Badia, 2013) aim at broadening modern VR rehabilitation approaches to include patients with different prognostic (motor and cognitive) and provide low cost at-home rehabilitation solutions for all. The RehabNet framework and methodology is based on improving: (1) accessibility of patients to the treatment through different interfaces; (2) patient compliance with therapy with the use of VR and Serious Games; (3) understanding of the technological and neuroscientific underlying mechanisms that affect therapy's effectiveness. However, the role and the effects of the type of interface in VR systems for neurorehabilitation are unclear with no previous literature to support the relationship between cognitive profile and type of interface. In fact, a recent review with an emphasis on evidence of VR technologies' efficacy rises concerns about the benefits of sophisticated technology for upper limb rehabilitation (Fluet and Deutsch, 2013). Thus, the specific benefits over conventional therapy of approaches such as robots, immersive vs. non-immersive VR, and 2D vs. 3D still remain unclear. Here we address the effect of different interfaces for VR interaction in a virtual task for rehabilitation combining cognitive and upper limb motor re-training. This research attempts to identify and understand the effect of different types of low-cost interfaces in both cognitive and motor performance in a VR task. We specifically address the effect of the nature of the interface (traditional interface vs. natural user interface), and the effect of dimensionality (2D movement on a table surface vs. 3D movement without arm support). In this paper we present preliminary data of an ongoing comparative study with healthy participants and stroke survivors using the RehabNet approach.

## 2. METHODOLOGY

### 2.1 Virtual Reality Motor and Cognitive Dual Training Task

RehabNet, a toolset developed for motor and cognitive neurorehabilitation, was used for implementing a dual motor and cognitive training task in both a clinical and non-clinical environment (Vourvopoulos et al, 2013). The software suite is composed by a Control Panel (RehabNetCP) that integrates a large number of commercial and experimental interface devices to enable the patient-task interaction within VR.



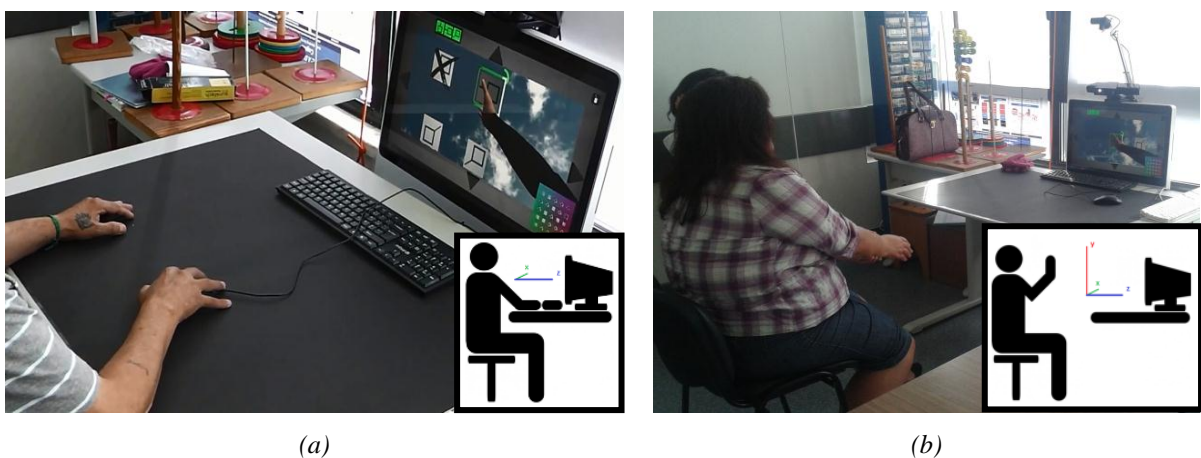
**Figure 1.** Virtual-reality motor and cognitive dual-training task. (a) Experimental setup including the (1) mouse, (2) Airmouse, (3) Kinect, (4) camera interface technologies. (b) VR Toulouse-Piéron task. The virtual environment shows a representation of an arm with an active timer over a selected tile.

The dual VR task was inspired by a well-established cancellation task, the Toulouse-Piéron task (Toulouse, Piéron, and Pando, 2004), in the following referred as TP-VR. The VR implementation includes a first person

virtual representation of the paretic arm, which is controlled via the RehabNetCP through various interfaces (see Figure 1a). The virtual environment is composed by a grid of 25 tiles with different symbols, navigation arrows at the edge of the screen, a mini-map, and 3 target elements (out of a total of 9) in green (see Figure 1 b). By means of physical movements and the use of different interface technologies, users can control the position of the virtual paretic arm on the screen. The selection of each tile is performed with the use of a timer while the virtual arm is hovering over. Consistent with the original Toulouse-Piéron task, the score is calculated with the following formula:

$$Score = [Correct - (Wrong + Omissions)] * 100 / TotalTiles \quad (1)$$

In this experiment, we decided to explore the effect of the use of Traditional Interfaces (TI) vs. Natural User Interfaces (NUI's) in 2-dimensional and 3-dimensional work spaces (see Figure 2). As TI we selected a 2D and a 3D pointing devices (a mouse and the Airmouse respectively), and as NUI we selected 2D and 3D camera-based tracking technologies (AnTS and Kinect respectively). In order to personalise each user interface to the capabilities of the hemi-paretic arm of each patient, we developed a Range of Motion (RoM) calibration procedure. Hence, at the beginning of each session a calibration was taking place in order to adjust the game based on the patients' RoM. Conditions were randomised within the experimental sessions with each session including one interface only. Participants were not imposed any constraint in movement type or speed.



**Figure 2.** 2-dimensional (a) and 3-dimensional (b) experimental setups. Inset images show the user's position relative to VR system and the allowed movements.

## 2.2 Experimental Setup

The experimental setup was composed by a desktop computer (OS: Windows 7, CPU: Intel core 2 duo E8235 at 2.80GHz, RAM: 4Gb, Graphics: ATI mobility Radeon HD 2600 XT), running both the RehabNetCP and the TP-VR training task. The available interfaces for this assessment included a standard mouse (TI-2D), an RC11 Airmouse (TI-3D) (Measy Electronics Co., Ltd, China), a PlayStation Eye camera (Sony Computer Entertainment Inc., Tokyo, Japan) combined with the Analysis and Tracking System (AnTS) for the tracking of a coloured glove (NUI-2D) (Mathews, Badia, and Verschure, 2007), and Kinect (NUI-3D) (Microsoft Corporation, Washington, USA). A standard keyboard was also used for baseline measurements. Data acquisition, filtering, logging were performed by the RehabNetCP and sent to the virtual environment via a UDP network connection. The virtual environment was developed using the Unity 3D game engine (Unity Technologies, San Francisco, USA). For all conditions regardless of the interface being used, the Kinect skeletal tracking was also used to assess user's kinematics. Thus, Kinect provided us with rich kinematic data for all interfaces for later comparison. The procedure was transparent from the participants' point of view and they were only required to use the different interfaces for crossing out targets on screen. For each session, the in-game data and user movement kinematics were stored for later analysis.

## 2.3 Participants

We performed a preliminary study consisting of a total sample of 66 training sessions from nine participants, three stroke survivors (1 male, 2 female), (age mean = 54, std = 15) and six healthy users (4 male, 2 female), (age mean = 30, std = 5.6). During a period of 1 month, each patient was exposed to an average of 12 training sessions with different interfaces, and healthy participants to 5 training sessions in one day. The clinical scales to determine the level of cognitive severity included (Table 2): The Addenbrooke Cognitive Examination - Revised

(ACE-R) (Mioshi, Dawson, Mitchell, Arnold, and Hodges, 2006) (Firmino, Simões, Pinho, Cerejeira, and Martins, 2008), covering a wide range of cognitive impairments incorporating five subscales (attention, memory, verbal fluency, language and visuo-spatial capability). The clinical scales to determine the level of motor severity of the hemi-paretic arm included: the Fugl-Meyer assessment, the Barthel Index. The Fugl-Meyer assessment adapted to evaluate the upper-limb (Gladstone, Danells, and Black, 2002). Stroke patients were selected at the Physical Medicine and Rehabilitation Department of Nélío Mendonça Hospital (Funchal, Portugal) according to the following criteria: ischemic stroke; at least 2 years of schooling; stroke event with less than a year; arm hemiparesis; no hemi-spatial neglect; sufficient cognitive ability in order to understand the training task instructions, as assessed by the MMSE  $\geq 15$  included in the ACE-R; 45 to 85 years old and motivation to participate in the study. The six healthy participants were students and staff from the University of Madeira and were recruited at the Madeira Interactive Technologies Institute. This study was approved by the ethics committee of the Health Service of Madeira Autonomous Region and all patients signed an informed consent form.

**Table 1.** Patient profile for Cognitive, Motor and Activities of Daily Living.

		Patient 1	Patient 2	Patient 3
<b>ACE-R</b>	Total	78	93	57
	Attention	18	18	16
	Memory	18	25	11
	Verbal Fluency	7	11	6
	Language	25	23	13
	Visuo-Spatial	10	16	11
<b>Fugl-Meyer</b>	Upper-Limbs	50	24	48
	Sensibility	8	7	12
	Passive Movement	24	20	23
	Pain	24	16	22
<b>ADL's</b>	Barthel	80	85	80

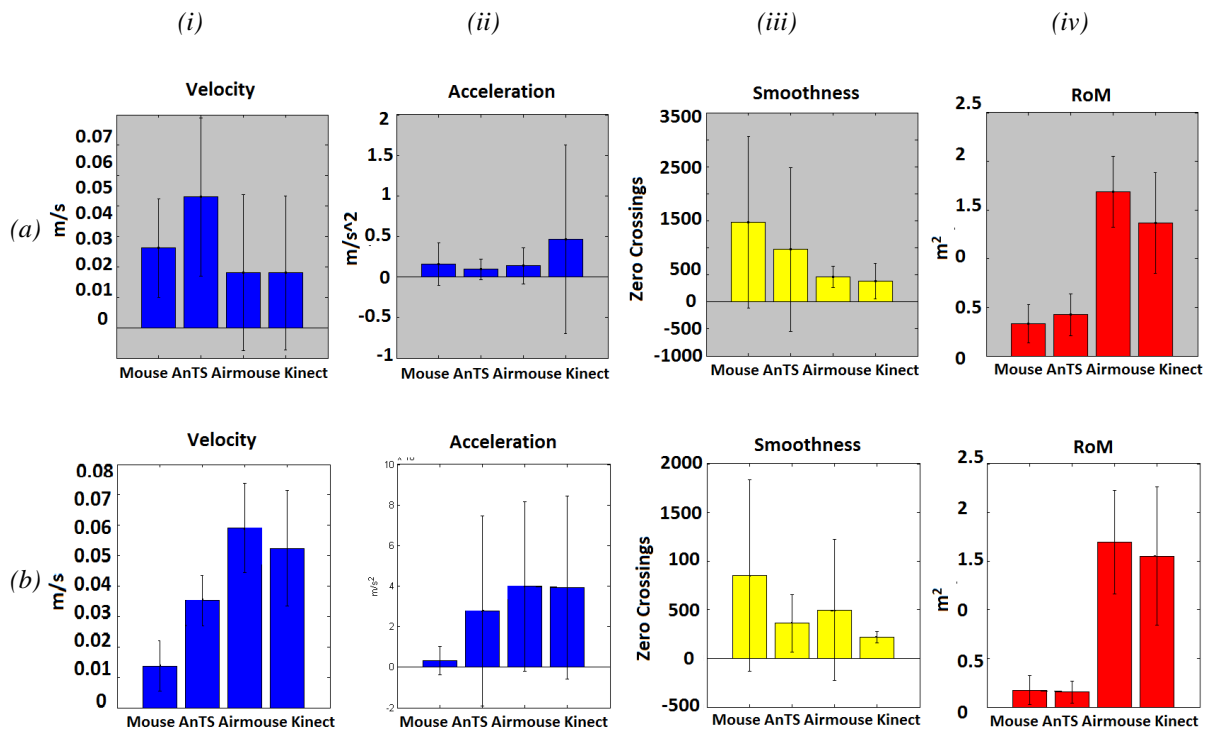
### 3. RESULTS

Data from 66 training sessions were gathered. Kinematics (captured through Kinect) and game data (task events in TP-VR) were synchronously logged to an XML file and parsed to Matlab (MathWorks Inc., Massachusetts, US) for analysis after each session. Kinematic data were initially cleaned from artefacts. Positional data were smoothed through Gaussian filtering window (60 seconds length,  $SD = 5$ ) and the average velocity (m/s), acceleration ( $m/s^2$ ), RoM ( $cm^2$ ), and Smoothness Index (SI) (number of acceleration minima) was calculated. The in-game data of the TP-VR task included the overall scoring (in %, equation 1), the task duration (in seconds), and number of mistakes. These data provided information of the patient's behaviour within the VR environment together with the acquired movement kinematics.

#### 3.1 Motor Domain

Figure 3 illustrates the data for both healthy and stroke participants in the motor domain (kinematic information). It can be observed that the average velocity of the patients' movements does not display differences among interfaces except for AnTS (NUI-2D), which is twice faster (0.043 m/s) compared to both 3D interfaces at ( $\sim 0.020$  m/s) (Figure 3a,i). For healthy participants there were clear differences based on the interface, being 2D interfaces slower than 3D (Figure 3 b,i). However, movement velocities achieved with both 3D interfaces (Airmouse and Kinect) are comparable. No differences can be observed for movement acceleration, neither patients nor healthy participants (Figure 3 ii).

As for movement smoothness, patient data shows higher SI (the higher the SI count the less smoother the movement) for 2D than for 3D interfaces (Figure 3a,iii). However, a different trend is observed for healthy participants, showing smoother movements for NUI than for TI (Figure 3b,iii). Finally, for RoM there is a clear distinction between the 2D vs. 3D interfaces for both patients and healthy participants (Figure 3,iv). In this case, 3D interfaces push participants towards wider movements that can go up to 1m larger than 2D movements.



**Figure 3.** Motor domain bar-plots for (i) Velocity, (ii) Acceleration, (iii) Smoothness Index and (iv) Range of Movement (RoM) from (a) patients and (b) healthy participants. Bar height indicates mean value, and the whiskers indicate standard deviation.

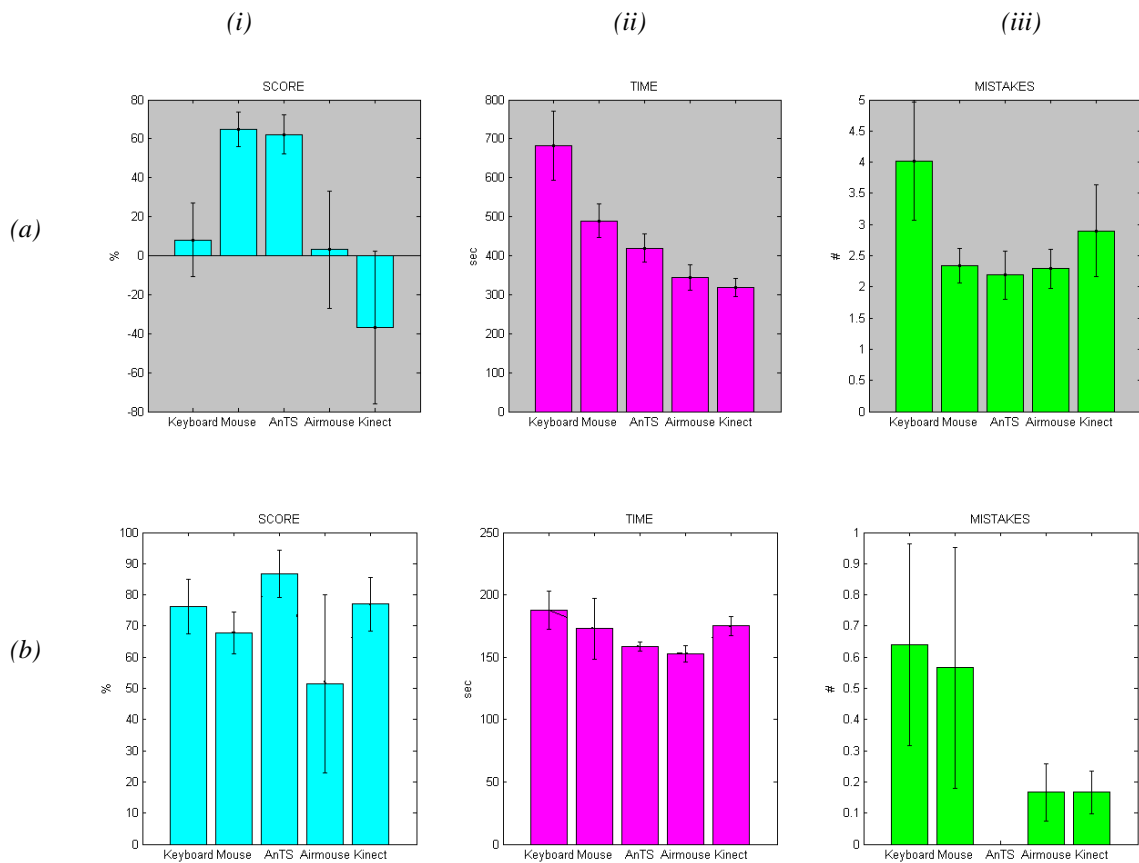
### 3.2 Cognitive Domain

Figure 4 illustrates the data in the cognitive domain for both stroke patients and healthy participants for all four tested interfaces plus the keyboard. In the case of patients, the task score is higher for both 2D interfaces (mouse and AnTS with a mean score of 64.9% and 62.2% respectively) whereas scores with 3D interfaces is close to 0% or even negative, that is, more mistakes than correct answers (Figure 4 a,i). Task scores for healthy participants are higher than those of patients, being NUI interfaces better compared to TI (Figure 4 b,i). When we analyse the time for task completion we can see that there is a clearer trend for patients than for healthy participants (Figure 4 ii). For patients longer times can be found for baseline (keyboard) and 2D interfaces, being shorter towards the 3D interfaces with Kinect being the fastest. Finally, it can be seen that patients perform more mistakes when using the keyboard and the Kinect than for the remaining interfaces (Figure 4 a,iii). Instead, for healthy participants it can be observed that the least mistakes were on the 3D interfaces (Figure 4 b,iii).

### 3.3 Interface Comparison

In order to be able to combine all motor and cognitive performance measures into a comparative analysis we ranked (between 1-4 for motor and 1-5 for cognitive, being higher a better outcome) the previously presented results (Table 2). Thus, based on the nature of the interface (TI vs. NUI and 2D vs. 3D) we can quantify their contribution towards objective cognitive and motor performance metrics. For example, in the motor domain higher velocity, larger RoM, and smoother movement (lower SI) are desirable. Likewise, higher scores, shorter completion times and fewer mistakes are preferable in the cognitive domain.

The ranking analysis in the motor domain shows that for patients 3D interfaces are preferable in terms of acceleration, smoothness, and RoM, whereas with 2D interfaces we find the fastest movements (Table 2a, motor). As a result the Kinect is the best globally ranked interface (rank sum = 13). For healthy participants we find that 3D interfaces systematically provide the best motor outcomes, being the Airmouse and Kinect ranked the best with a rank sum of 14 and 13 respectively (Table 2b, motor). In the cognitive domain there is no clear interface outperforming the others in all metrics. 2D interfaces provide the best task scores but also the slowest task completion times (Table 2a, cognitive). In the case of healthy participants, there is a clear preference in the cognitive domain towards NUI (either 2D or 3D), providing both a rank sum of 12 (Table 2b, cognitive).



**Figure 4.** Cognitive domain bar-plots for (i) Score, (ii) Time, and (iii) Mistakes from (a) patients and (b) healthy participants. Bar height indicates mean value, and the whiskers indicate standard deviation.

**Table 2.** Ranking of interfaces according to motor and cognitive performance metrics from (a) patient and (b) healthy data. The higher the ranking the better performance.

		(a) Patients					(b) Healthy				
		2D		3D			2D		3D		
		Keyboard	Mouse	AnTS (NUI)	Airmouse	Kinect (NUI)	Keyboard	Mouse	AnTS (NUI)	Airmouse	Kinect (NUI)
Motor	Velocity	3	4	1	2	1	2	4	3		
	Acceleration	3	2	1	4						
	Smoothness	1	2	3	4						
	RoM	1	2	4	3						
Total		8	10	9	13		5	8	14	13	
Cognitive	Score	3	5	4	2	1	3	2	5	1	4
	Time	1	2	3	4	5	5	3	2	1	4
	Mistakes	5	3	1	2	4	1	2	5	4	4
Total		9	10	9	9	10	9	7	12	6	12

### 3.4 Multi-linear Regression Data Modelling

Following the above qualitative analysis, a more quantitative approach is necessary to understand better the impact of our experimental variables on the motor and cognitive domains. We decided to use a stepwise multi-linear regression modelling approach for detecting and quantifying the effect of the experimental independent variables on the dependent ones. Our independent variables include interface, TI or NUI, and user demographics (user type, gender, age). The dependent variables in the motor domain include velocity, acceleration, range of movement, and smoothness; and in the cognitive domain include score, time to completion and number of mistakes.

**Table 3.** Multi-linear stepwise regression model. The table shows the coefficients of the independent variables that have a significant contribution in the regression model for all metrics in the motor and cognitive domains and the R square values.

		User Type	Gender	Age	Interface	Interface Type	Dimension	R-Sq
Motor	Velocity						0.0295	0.52
	Acceleration	-1.58E-10						0.14
	Smoothness				-368.579			0.19
	RoM						1.5366	0.77
Cognitive	Score	16.3564						0.11
	Time	-114.5528						0.59
	Mistakes	-1.3194					-0.345	0.92

Table 3 summarises the modelling findings. In the motor domain we find that the dimension of the interface has a significant contribution towards determining the velocity of the movement ( $Coeff. = 0.029, p < 0.001$ ). 3D interfaces generate faster movements, probably due to the fact that 3D movements are more ballistic in comparison to movements on a surface. The acceleration of upper limb movements is significantly affected by the type of the user ( $Coeff. = -1.58e-10, p < 0.05$ ), where healthy participants have higher acceleration values than patients. The smoothness of movement is significantly affected by the choice interface ( $Coeff. = -368.58, p < 0.05$ ). In this case, 3D interfaces contribute towards smoother movements. Finally, the dimensionality of the interfaces (2D vs. 3D) significantly contributes to the RoM ( $Coeff. = 1.54, p < 0.001$ ). In the cognitive domain, for all dependent variables we find a significant contribution of the user type (patient vs. healthy participant): score ( $Coeff. = 16.36, p < 0.05$ ), time ( $Coeff. = -114.55, p < 0.001$ ), and mistakes ( $Coeff. = -1.32, p < 0.001$ ). It can be seen that healthy participants perform better and resolve the task faster and with less mistakes. Finally, we find a significant contribution of the dimensionality of the interface (2D vs. 3D) in the number of mistakes ( $Coeff. = -0.34, p < 0.001$ ), performing less mistakes with 3D interfaces.

#### 4. CONCLUSIONS

This research aims towards the development of VR technologies for the inclusion of all patients into VR neurorehabilitation therapy, accommodating both software and hardware aspects of the technology. In this project, both stroke survivors and healthy participants have used four different computer interfaces for virtual environment interaction in order to gather insights on how the choice of interface in a neurorehabilitation task affects outcomes in the motor and cognitive domains.

Our results indicate that patients perform faster upper limb movements by using 2D interfaces whereas healthy participants are faster by using 3D. This can be an indication that patients can interact faster when they support the paretic arm on a surface rather moving it within the 3D space, and as a result, promoting a more stable way for interaction. Consistently for patients and healthy participants, 3D interfaces contributed towards smoother movements as quantified by the Smoothness Index (SI). This could indicate that 3D interfaces generate smoother movements because there is no friction with a surface that may affect the quality of the movement. Finally for RoM, 3D interfaces seem to contribute towards the exploitation of movements in a larger space than 2D interfaces. However, overall NUI render better motor performance. Consequently, depending on the specific desired outcomes from training, a 2D-3D or TI-NUI interface may be preferred. In the cognitive domain, we found that better scores come at the expense of longer completion times, and shorter completion times at the expense of mistakes. Our findings verify the observed situation where the patients get tired faster when using a 3D interface, leading to faster termination of the session. Furthermore, traditional interfaces contribute towards better scoring but at the expense of poor motor performance. Consequently, the challenge is in identifying the best trade-off between the two domains in order to provide each patient with the best possible rehabilitation solution, taking into account their specific motor and cognitive re-training needs. Thus, AnTS, a 2D-NUI interface, seems to be the preferred compromise for patients.

The large variability in cognitive function of the participants as assessed by the ACE-R, may have been the cause behind the lower accuracy of the score variable in the multi-linear regression model. However, this variability did not compromise the accuracy of the other models in the cognitive domain such as time or mistakes. Another possible limitation of the study is an eventual learning effect during the 4 week/12 sessions experimental period. Since no intermediate evaluation took place, this was minimized by randomizing the

exposure to the interfaces. Finally, despite the small sample size of this pilot experiment, we believe that such a quantitative approach can provide useful pointers towards the design and deployment of future VR and rehabilitation systems taking into account both cognitive and motor domains.

In this pilot study we introduced a novel approach towards virtual rehabilitation to identify the particular benefits of interfaces and their characteristics on cognitive and motor performance. The ultimate goal of the RehabNet approach is to widen the spectrum of patients that can benefit from virtual rehabilitation, for in-home or clinical environments. Current target is to extend this study to gather data from more stroke survivors and also extend the analysis to include motor and cognitive clinical evaluations. This may allow us to find correlates between clinical evaluations and motor and training outcomes that will enable us to derive general and yet specific guidelines for the selection of interfaces in virtual neurorehabilitation. In the future we aim to extend the RehabNet to incorporate brain-computer interfaces to enable motor and cognitive training in patients with very low or no mobility.

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