Bespoke Video Games to Provide Early Response Markers to Identify the Optimal Strategies for Maximizing Rehabilitation

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ABSTRACT

Monitoring recovery during illness informs future intervention strategies and so is pivotal in determining patient outcomes. Markers are commonly used in such a process, with such markers usually derived via laboratory based biological sampling. However, some conditions rely solely on markers derived from physical observation. Recovery from stroke is a condition where monitoring is carried out via a therapist observing a patient's motor learning skills. This is time consuming and costly due to the requirement of a therapist and the patient to meet throughout the recovery lifecycle. In addition, error is introduced as different therapists may interpret motor learning differently. In this paper, we attempt to alleviate these issues by employing a bespoke video game to derive markers to identify strategies for rehabilitation without therapist intervention. Although video games (or any encouraged physical activity) have been shown to aid in rehabilitation, this is the first time the evaluation of early response markers has been derived in this manner.

Categories and Subject Descriptors
J.3 [LIFE AND MEDICAL SCIENCES]: Health

General Terms
Measurement, Design, Experimentation, Human Factors

Keywords
Rehabilitation, video games, motor learning

1. INTRODUCTION

Stroke is a major global problem; the current prevalence of 60 million stroke survivors is predicted to rise to 77 million by 2030. Hemiparesis, a detrimental consequence that many stroke survivors face is the partial or complete paralysis of one side of the body that occurs due to the brain injury. It is remarkably prevalent occurring acutely in 80% [1, 2]. Unfortunately, upper limb recovery is unacceptably poor with persisting impairments in 50-70% of stroke survivors [2, 3]. Although it has been established that intense rehabilitation therapy increases upper limb recovery, resource limitation is the main barrier to implementation of this evidence-base. Given the increasing prevalence of stroke survivors, it is a priority to identify the most effective rehabilitation strategies and/or pharmacotherapies that augment neuroplasticity in order to maximise a patient's response to the available therapy time.

Motor learning is the essential process underpinning recovery after hemiplegia, either through relearning to use the paretic arm and hand and/or learning to compensate with the lesser-affected side. Furthermore, motor learning in normal subjects and functional neuroplasticity leading to post-stroke motor recovery have been shown to share the same underlying molecular and genetic substrates and brain networks [4]. Since motor learning can be assessed more quickly and more robustly than behavioural outcomes from rehabilitation of stroke survivors, assessment of performance and motor learning can provide an ideal marker of the biological system underpinning rehabilitation.

In this paper we describe a proof of concept system that utilises a bespoke video game to generate high spatial-temporal resolution data from players. Such data is key to measuring the critical components of motor learning that in turn provide early response markers. We demonstrate how our system is sufficiently sensitive to detect how simple changes in therapist instruction significantly influence the motor performance exhibited within in-game player performance.

The literature presents numerous works indicating how serious games may aid in rehabilitation. However, the main focus of this paper is not to provide a rehabilitative game (where encouraging while recognising broad movement is sufficient), but to show, for the first time, an ability to measure early response markers to a clinical standard that are key to informing rehabilitative strategies. Such markers would otherwise be derived through time consuming, and costly, therapist observation.

The capacity to automate evaluation brought about by the utilisation of the approach described in this paper brings forward additional opportunities in allowing targeted screening of candidate drugs for repurposing into rehabilitation, prior to initiating phase 2 or phase 3 trials, or patient stratification for clinical trials, based on level of performance and indices of motor learning.

2. System overview

Nearly all manipulation activities of daily living require the ability to flexibly perform multiple steps to achieve a unitary task. Thus, regaining the ability to perform efficiently linked action phases in manipulation tasks is highly important for rehabilitation. In this paper we illustrate the use of the proposed system to assess whether the instructions given by a therapist to subjects learning a task requiring two action phases, either describing the task as having a single objective or by breaking the task down into its two sequential action phases, significantly affects performance and learning.

2.1 Bespoke video games

We have developed a series of bespoke video games that require learning of sequentially linked action phases and capture key features of natural manipulation tasks, namely spatial and temporal control and the requirement that each phase is completed before the next phase can be executed. Furthermore, each action phase utilises characteristics of movements performed in real life (controlled application and adaptation of forces, visuomotor integration and adaptation, feed forward planning and feedback correction).

The game used in this evaluation involves moving a spacecraft (avatar) around a screen to avoid and/or destroy meteorites (targets). A patient controls the movement of the avatar via isometric forces applied to a joystick. In essence, the patient must move their avatar to the same location as a target when it appears. The avoid/destroy are gameplay elements acted out onscreen to increase interest for the patient.

Two sequentially linked action phases (transfer phase and lock and track phase) are embedded in the game. Players initiate a trial by relaxing their hand to bring the avatar to a central home zone. Targets are then randomly presented at one of three locations, namely to the right, to the left, or centrally above the home position. The first phase comprises moving the avatar towards the target (transfer phase), once having achieved the target the player must then hold the avatar within the trajectory of the target for 1s (lock and track phase). Feedback of performance is provided as a score that builds up on the screen during each trial of 12 target presentations. The final score is then presented at the end of each trial.

2.2 Monitoring play

The joystick chosen was a Saitek Pro Flight X-65F Combat Control System (PC) Joystick. This joystick is considered a "high-end" gaming device costing approximately $500. However, unlike the typical joystick most gamers are familiar with, the Saitek Pro Flight does not measure the degree of movement of the joystick itself (typically found in controllers for consoles such as PS3, and Xbox). Instead, the pressure and the direction of such pressure are measured (the joystick is actually unmoveable). For the purposes of our game we are concerned with the joystick measurements associated to kilogram-force (*kgf*), and the degree to which this force is measured in the x axis (left or right on joystick) and y axis (up and down on joystick).

Understanding how the joystick works is important for realising the actions patients are required to undertake to successfully complete the game. The joystick informs the game of both force and position via a kgf value in both the x and y coordinate. This is then mapped into 2D space {x, y} floating-point coordinates between 1 and -1 to represent points that exhibit both direction and magnitude (which is the force). Assume figure 1.a indicates the joystick at rest (no force applied) and the outer circle represents the most force the joystick could recognise in all x and y directions. Figure 1.b indicates force applied in the negative x (left) and positive y (up) directions. Figure 1.c indicates a more severe force than that applied in 1.b (due to its proximate to the outer circle) in the positive x (right) and negative y (down) directions. Therefore, a steady force maintained in a single, unwavering, direction will provide an unmoving cursor at some point, say {Px, Py}, with the distance from the origin {0, 0} indicating force (relative to the maximum force achievable).

To ultimately accommodate patients with movement difficulties the joystick has been adapted so forces orientated to the right, to the left, up or down can be generated by movements of the supported, out-stretched hand and/or by the arm and shoulder. The patient does not grip the joystick, but rests their hand on a custom made support on top of the joystick. This allows patients with severe disability to apply pressure and participate in the game. The pressure generates an {x, y} coordinate indicating force and direction (as mentioned earlier). A translation is applied to these coordinates to map them to "screen space".

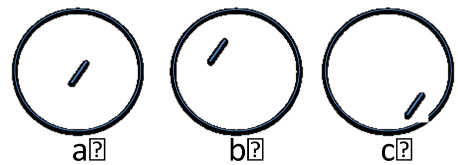

Figure 1 - Joystick representation of force and direction

Screen space is not circular (reachability of {x, y} by joystick), and represents the resolution of the game graphics (1280 pixels wide by 800 pixels in height). Therefore, a basic scalar translation is applied to enlarge the joystick {x, y} coordinate beyond that of the screen area. As the derived coordinates of x and y generated by the joystick is a floating-point number between -1 to 1 in both x and y, this can be achieved by multiplying x and y by 1280 and casting to integer values (for pixel alignment). If full force could be achieved this could result in y coordinates occurring "off-screen" (i.e., beyond 800 and -800). However, this does not occur as input from the joystick relating to magnitude/force (distance from origin) is capped to retain the avatar in-screen.

2.3 Capturing data

Assuming that each hand will deviate in ability due to stroke the game calibrates separately for each hand. This allows further refinement of the coordinate system. The side more severely affected will not be able to reach the same degree of coordinates as the less affected side. Therefore, calibration takes this into account and applies an appropriate ratio to allow the same degree of "on-screen" movement for both hands. For example, if the left side can only apply a maximum of 5 kgf whereas the right side can apply a maximum of 20 kgf, then the left phase of gameplay will apply a 4:1 ratio multiplier to attain the same degree of movement on the screen.

Theoretically, when a target (meteorite) appears it is possible to apply the correct force and direction to the joystick so as to make the avatar appear immediately over the target. This is because we are not "moving" in the direction indicated by the joystick, rather we are placing the avatar on screen as directed by the {x, y} coordinates produced by the joystick. However, as humans naturally take time to react and build up force the avatar appears to move across the screen.

To achieve an appropriate fidelity of sampling to ensure no significant movement data is missed we sample the joystick at 500 times a second and update the game loop at the same rate (500 times a second). A commercial video game typically runs at 60 frames a second. However, our desire for a much higher rate is driven by the desire to rule out the loss of outlier measurements (sudden increase or decreases in pressure) that may occur. This also has the result of allowing a high fidelity of movement data to be considered within the gameplay itself, allowing the data that is used clinically to drive the game. Although the monitor/TV cannot show 500 full frames a second, we can still run the game at such a rate for accuracy of tracking the joystick and refresh the screen as and when required.

Accuracy tracking per-target is calculated as the mean distance the joystick {x, y} is from the actual target coordinates over the time the target is present. This measurement is returned to the coordinate system between (-1, 1) to trivialise comparisons across all targets. Time (as presented in the graphs) is measured in seconds.

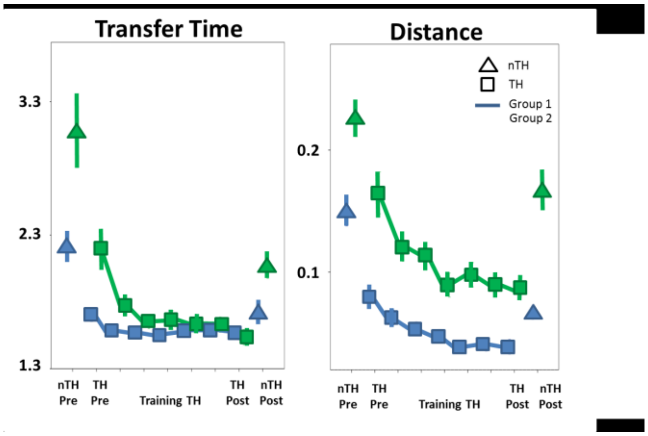

Figure 2 - Graphs derived from game data; learning curves for transfer time (s) and distance. For analysis the data for every three sequential trials are grouped. The blue symbols indicate Group 1 (perceived single objective) and the green symbols Group 2 (perceived 2 step task). The squares indicate the trained right hand (TH) and the triangles the non-trained left hand (nTH). The error bars are SEMs. For both indexes lower values are associated with higher performances.

2.4 Analysis system

Prior to starting the game each player undertakes a calibration procedure. The maximum pressure that the subject is able to generate by rotating their hand to the right or left and by palmer flexion is recorded for each hand separately. The pressure required in the task to reach the target at each position is then automatically set to be 10% of maximum respective pressure, to avoid fatigue during game play.

1) *Transfer Time* - the time between the appearance of the target on the screen and the avatar reaching the target. This index reflects predominanty feed-forward generation of movement with little opportunity to correct errors based on feedback.

2) *Distance* - the mean distance between the target and the avatar during the lock and track phase. This index reflects predominantly feedback mechanisms and error correction.

For both indexes lower values are associated with higher performances.

3. Method

The ethical committee of approved the study and written informed consent was obtained from participants. All participants were naïve to the experimental setup and objectives of the study.

3.1 Subjects

We compared two groups of 12 right-handed, young adult subjects (Group 1: mean age, 27 years, range 20-35 years; Group 2: mean age, 27 years, range 20-36 years). The video games, the controllers used and the environment in which the game was played were the same for both groups.

Group 1 (Single objective instruction group) were asked to play the videogame with the single instruction to follow the target as accurately as possible; the feedback score reflected the accuracy of tracking the target.

Group 2 (Two step instruction group) were asked to play the video game with the instructions to move the avatar to the target and then to follow the target as accurately as possible. The feedback score for this group reflected both the time taken to transfer the avatar to the target and the accuracy of tracking thereafter.

3.2 Protocol

Initially the subjects play three trials within the game with each hand (non-dominant hand first) to assess their pre-training performance levels. This is followed by a session of training for the dominant hand, when the player undertakes 15 further trials. After completing training, the player undertakes a final 3 trails with their dominant (trained) hand to determine their post training performance levels. This is followed by 3 trials with their non-dominant hand (un-trained hand) to assess inter-limb transfer of skill from their trained to their untrained hand (a measure of generalisation of learning).

3.3 Data analysis

Pre and Post training performance for each hand was assessed as the mean *Transfer Time* and the mean *Distance* for the first and last 3 trials respectively. Motor learning was assessed as the difference between pre training performance and post training performance for the trained hand. Inter-limb transfer of training from the trained hand to the non-trained hand was assessed as the difference pre and post training performances for the untrained.

3.4 Statistical analyses

The data was normally distributed. Significance was set at $p<0.05$, with Bonferroni correction. A General Linear Model Repeated Measures Analysis of Variance (ANOVA) was used with Greenhouse-Geisser correction if required (SPSS 15, SPSS Inc, Chicago, Illinois, USA). Each hand (trained hand, non-trained hand) was analysed separately. *Time* (Pre, Post Training,) was the within-subject factor; *Group* (Single, Double instruction) was the between-subject factor.

4. Results

4.1 Trained hand (TH)

There was a main effect of *Group* for Distance ($p=0.012$), with a significantly better performance in Group 1 (perceived single objective) than Group 2 (perceived two step task). There was a main effect for *Time* for both indexes ($p<0.001$ for Transfer time and Distance), indicating motor learning for both groups. Whilst there was no main effect of *Group* for Transfer Time ($p=0.256$), there was a significant *Group*Time* interaction ($p=0.015$) with a trend towards a better performance for Group 1 (perceived single objective) prior to training ($p=0.089$) but no difference between groups after training ($p=0.831$).

4.2 Non-trained hand (nTH)

There was a main effect of *Group* for both indexes (*Transfer Time,* $p=0.034$; *Distance,* $p=0.001$) with significantly better performance for Group I (perceived single objective) both pre and post training. There was also a main effect of *Time* in both indexes (*Transfer Time,* $p<0.001$; *Distance*, $p<0.001$) indicating inter-limb transfer of dominant hand training occurred in both groups for both components of the task. A significant *Group*Time* interaction was observed in the Transfer Time index ($p=0.040$) with greater transfer in Group 2 compared to Group 1.

5. Discussion

In almost any training situation where action goals are to be learnt, including rehabilitation after stroke, instructions are given. In the present study we presented to both groups exactly the same sequences of stimuli and in response the participants performed the same two sequentially linked action phases. When the instructions and feedback emphasised the two subcomponents of the task rather than focusing on the single action goal (tracking the target), the performance of both action phases was significantly degraded. These findings add to a growing literature that the nature of the instructions given has a decisive influence on performance and/or learning of the action goal. For example, there is converging evidence that an external focus for instructions (i.e., a focus on the movement effect) is more effective than an internal focus (i.e., focus on the muscles activated to achieve components of the movements themselves) for both performance and learning (for review see [5]). In this study the two groups were given an external focus since both instructions focused on the desired movement effect.

The task studied in the present study involved two sequentially linked action phases. Although most manual tasks involved in activities of daily living comprise sequentially linked action phases, nearly all studies of manual control and learning concern single actions, such as simple reaction times or moving the hand between two positions. Thus, our understanding of how action phases are linked to perform the overall action goal, and how such linking affects learning, is limited.

Bernstein [6] first argued that action goals correspond to a pattern to be executed in external space rather than a sequence of specified muscle patterns. An easily verified demonstration that action goals are abstract pattern is that one's written signature has the same unique pattern whether generated by shoulder and arm muscles to write on a blackboard or by forearm and finger muscles to write on paper [7].

Klapp and Jagacinski [8] summarised recent research that supports action goals being represented as an abstract code that does not incorporate details of the sub-components required, but rather involves a single motor gestalt or chunk that is processed holistically. Additional findings indicate that the organization of action goals into chunks can be changed by instructions. For example, when reaction time was measured prior to the articulation of pseudowords [9] instructions that encouraged separate articulation of each of the syllables resulted in reaction times that increased as a function of the number of syllables. However, when the instructions favoured combining the syllables to form a single word, the reaction time did not increase as a function of the number of syllables implying that combining the syllables created a single motor gestalt so that the number of chunks is one, regardless of the number of syllables.

The results of our study mirrors these findings but in relation to a manipulative task; the transfer time was prolonged when the instructions favoured viewing the action goal as two separate tasks rather than as a single action goal. Furthermore, not only was the transfer timing prolonged but the accuracy of the tracking task was degraded, when the action goal was viewed as two separate tasks. These results support the concept that motor action goals might be represented as a single motor gestalt and indicate that task boundaries defining a motor chunk or single motor gestalt are not inherent to the action goal, but are ultimately determined by participants' subjective representations of the task, shaped by the instructions given.

6. Conclusion

Video games have been shown to encourage stroke rehabilitation due to the simple fact that they require concentration of thought and some form of physical exertion (e.g., [10] [11]). However, there has not been a clinical view to deriving the required early markers to inform intervention, as described here, directly from the gaming hardware itself (in our case the joystick). Our most recent work [12] demonstrates an ability to determine change using video game devices benchmarked against therapist intervention. However, this paper goes further and investigates the validity of using off-the-shelf hardware coupled with bespoke video games to gain early response markers in the case of stroke rehabilitation.

This study provides proof of concept that video games and automated analysis systems can provide the capability to rapidly evaluate even subtle aspects of rehabilitation strategies, such as the content of instructions. We propose to develop a library of action phases, which can be easily combined and incorporated into bespoke video games together with automated data extraction and analysis to provide a flexible system for early response markers for evaluation of rehabilitation efficacy.

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