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The use and effect of video game design theory in the creation of game-based systems for upper limb stroke rehabilitation

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Abstract

Upper limb exercise is often neglected during post-stroke rehabilitation. Video games have been shown to be useful in providing environments in which patients can practise repetitive, functionally meaningful movements, and in inducing neuroplasticity. The design of video games is often focused upon a number of fundamental principles, such as reward, goals, challenge and the concept of meaningful play, and these same principles are important in the design of games for rehabilitation. Further to this, there have been several attempts for the strengthening of the relationship between commercial game design and rehabilitative game design, the former providing insight into factors that can increase motivation and engagement with the latter. In this article, we present an overview of various game design principles and the theoretical grounding behind their presence, in addition to attempts made to utilise these principles in the creation of upper limb stroke rehabilitation systems and the outcomes of their use. We also present research aiming to move the collaborative efforts of designers and therapists towards a model for the structured design of these games and the various steps taken concerning the theoretical classification and mapping of game design concepts with intended cognitive and motor outcomes.

Keywords

Video games, stroke, rehabilitation, game design theory, upper limb

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Introduction

In the United Kingdom, stroke is the single biggest cause of disability[1] and there are around 150,000 first-time strokes every year.[2] Some 80–85% of survivors[3,4] are affected by hemiparesis and only 5–34% eventually regain complete functionality of their upper extremity (UE).[5] Immediate hospital-based physiotherapy can capitalise on spontaneous recovery,[6] with 80% of recovery said to occur within the first 6 weeks.[7] However, hospital-based exercise programmes are costly,[8] resulting in shorter average inpatient stays: 23.7 days in 2008 to 19.5 days in 2010 in the UK,[9] for example. In addition to this, not only are patients spending less time in hospital but it would also seem that staff are stretched, with just 42% of physiotherapy, 16% of speech and language therapy and 84% of occupational therapy services meeting the stroke strategy staffing guidelines.[10] Furthermore, increasing lower limb movement is often a higher priority to enable discharge than increasing upper limb movement, meaning the hospital stay is often focused exclusively on improving mobility, posture, balance and gait.[11] In a 2014 study, only ~22% of health care professionals (out of 264) and ~17% of patients and carers (out of 123) agreed or strongly agreed that there is "good arm and hand therapy in hospital".[12] Because of these problems, self-management approaches are an attractive prospect[13] if a patient's care can be supported by home-based practice routines[14] focused on the previously

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omitted upper limb exercises. For the UE, rehabilitation is often focused on the improvement of performance in functional tasks through goal-directed practice and repetition.[15,16] Repetitive movements associated with specific skills, if intensive and able to deliver feedback, can promote neural plasticity and motor recovery.[17] One method, constraint-induced movement therapy, encourages use of the more-affected limb by constraining the less-affected limb and is effective in facilitating both immediate and long-term functional improvements.[18] Another, bilateral training, requires the patient to perform mirrored movements with both limbs and can also be advantageous for motor retraining.[19] These repetitive exercises can, however, be uninteresting and tedious, reducing motivation for sustaining treatment[20] both at home and in hospital. Game-based therapy can be used to augment the aforementioned therapy techniques,[21] helping fulfil various principles of motor learning,[22] and is a practice which is constantly gaining considerable ground in terms of becoming a widely accepted approach in the area. This article is motivated by the belief that the principles of game design described herein, namely meaningful play, feedback, goals, rewards, challenge, difficulty, failure and flow, can be as integral to the creation of custom-made games for stroke rehabilitation as they are to the creation of commercial games.[23] Games can be a powerful therapeutic tool when integrated into rehabilitation, although the critical focus and resulting discourse typically omits the important and very salient link between these principles and rehabilitation. This may be particularly true in terms of the merit in both their use and the understanding of them.

Why games for rehabilitation?

A recent Cochrane review assessed the effect of virtual reality (VR) treatment on the recovery of motor, gait, balance, cognitive functions and activities of daily living (ADL) in stroke patients, finding that, particularly for upper limb treatment, the VR approach yielded better functional outcomes than conventional therapy.[24] Playing games has been shown to have many positive behavioural and physiological effects, leading to meaningful improvements across cognitive, motor and affective measures.[21] Neurophysiologically, the increase in physical movement, opportunities for bilateral activity and augmentation of biofeedback can help to induce neuroplasticity.[25,26] Influencing neuroplastic adaptations in the brain following a stroke through behavioural/motor experience is important in protecting remaining neurons and producing/strengthening neuronal connections.[27,28] The full scope of the advantages of VR/game-based therapy has been discussed in previous research,[23,29,30] though one of the chief advantages is the enhanced motivation such interventions can grant across an ever-growing demographic,[31] increasing the amount of practice and, consequently, the degree of performance improvement.[32] It has been suggested that to effect any kind of cortical change, at least 20 hours of training,[33] or 300–400 repetitions of any one movement[34] are needed, although neuroplastic changes in primate brains have been shown to be the result of as many as 12,000 repetitions over 11 days.[35] Therefore, dependence on existing therapies alone in order to promote neuroplastic changes might not always be practical,[36] as these figures are far above what research submits are achievable dosages in clinical practice: 4 hours of training per week[37] and just 30 repetitions of a single movement in a traditional rehabilitation session.[38]

In upper limb rehabilitation discourse, both commercial and bespoke video games are attractive prospective tools. Their application has been explored since the arrival of ‘exergames’ in the 1980s[39] and the consequent and exponential creation of games without entertainment as the primary focus, often termed as ‘serious games’.[40] In games for rehabilitation, ecologically relevant functional movements can be masked within the context of the game and presented as steps to accomplish an objective.[23,29] For example, reaching, grasping, pulling and pushing movements were masked in the context of *Slingshot*, *Space Race* and *Balloon Pop* games for the ‘virtual glove system’.[41] In this manner, games for rehabilitation may also function as ‘persuasive’ games, a concept coined by Ian Bogost,[42] which states that games can be strong rhetorical tools in conveying ideas and altering the user’s interpretation of the kinds of activities or movements they invoke. The combination of less expensive, but higher-fidelity, technology has been facilitating a rise in the user acceptance and clinical validity of games for serious purposes, such as stroke rehabilitation,[43] although it has been suggested that the rapid pace of innovation provides a ‘moving target’ for researchers, presenting additional challenges.[44] Motivation is a hugely important factor in rehabilitation, often linked to better therapeutic outcomes, but is also a complex and difficult concept to describe.[45] It can be thought of as a psychological property that encourages a patient to elicit and/or sustain goal-directed behaviour,[21] and a motivated patient is one willing to expend effort without needing undue encouragement or complaining about the rigours of treatment.[46] We are intrinsically motivated when we find interest, enjoyment and satisfaction in an activity,[47] and the playing of games is fundamentally an intrinsically motivated activity.[48] Lack of motivation and slow progress have been noted as impediments for poor adherence to home-based practice,[49] although VR programmes deployed at home have reported improved user satisfaction and a marginal increase in performance.[50]

Commercial systems

Commercial games are attractive because of the overwhelming market-derived evidence that these games are effective at motivating individuals to use them,[21] and some may offer features suitable for stroke rehabilitation straight out of the box.[51] The Nintendo Wii and Sony PlayStation EyeToy have been two popular choices in the past, not least because of their low cost and the burgeoning research supporting their application.[25] Both systems have been used to play a number of commercial games, primarily *EyeToy: Play* (Sony) and *Wii Sports* (Nintendo), both collections of short, simple mini-games intended for children. Their simplicity reduces concern about cognitive overload[52] and attractive, bright graphics make them instantly relatable, although adult participants from one recent study did find the childlike aesthetics of *Wii Sports* unappealing.[53] In one study, statistically significant improvements in Fugl-Meyer Assessment and Motricity Index scores were noted after just six 30-minute sessions using *Wii Sports*,[54] while one of only a few randomised controlled trials in this area, which focused on the use of *Wii Sports* and *Cooking Mama* in comparison to recreational therapy involving table-top games, noted improved Wolf Motor Function Test scores for the Wii group at 4 weeks post-intervention.[55] User acceptance and functional improvement were also noted in several other smaller-scale studies.[56–59] While the Wii requires precise aiming and controlled motions, video-capture systems such as the PlayStation EyeToy can illicit gross, ongoing movements,[60,61] whilst allowing for more naturalistic, unencumbered interaction.[62] A randomised controlled trial analysed the effect of the EyeToy on 20 stroke patients over 4 weeks.[63] In addition to conventional therapy, one half received 30 minutes of treatment with the EyeToy, while the other half watched the games for the same duration. Significant improvements were noted in the experimental group via the Functional Independence Measure and the games were also deemed motivating and enjoyable, a feeling expressed in another study featuring the *EyeToy: Play* games *Wishy Washy* and *Kung Foo* and the IREX, a rehabilitation-specific video-capture gaming system.[64]

The more powerful Microsoft Kinect grants highly accurate[65] full-body motion tracking and gesture/scene recognition.[66] Due to the abilities of this device, much work with it has been in the creation of intuitive applications focusing on technical possibilities.[67] One trial did evaluate the games *Kinect Sports* (Rare) and *Kinect Adventures!* (Good Science Studio), aesthetically similar to the EyeToy and Wii games, with 14 chronic stroke patients[68] and found Kinect therapy helped improve Functional Independence Measure scores, plus shoulder and elbow flexion and extension. Sophisticated, modern technology like this, such as a sub-millimetre accurate[69] optoelectronic device called the Leap Motion Controller and especially touchscreens, are leading to 'Natural Interaction', a type of human–computer interaction which allows for faster, more accurate and more intuitive communication with game systems.[70] A popular commercial game which has been adapted for stroke patient use with both the Kinect and the Leap Motion is *Fruit Ninja* (Halfbrick Studios), which recently reached 1 billion downloads.[71] The game is traditionally played on touchscreen devices with the player swiping their finger across the screen, chopping up fruit as it is launched across. When used with the Kinect, Fugl-Meyer Assessment and Wolf Motor Function Test scores were significantly increased 3 weeks after training and at a 12-week follow-up, while functional magnetic resonance imaging (fMRI) results showed contralateral primary sensorimotor cortex activity, demonstrating functional neuroplasticity.[72] *Fruit Ninja* played with the Leap Motion yielded a high correlation between game scores and Fugl-Meyer Assessment/Box & Blocks Test scores in one trial[73] and improvements in hand abilities and grasp force in another.[74] Also, with the Leap Motion, a group recently created three virtual rehabilitation tasks: a virtual rendition of the *Nine Hole Peg Test*, *Cotton Balls* and *Stacking Blocks*.[75] All three were well received by the eight therapists that tested them, highlighting the possible usefulness of modern devices such as these in stroke rehabilitation.

The combined results of studies applying commercial games to rehabilitation are promising, not just in terms of their cost, safety and ability to elicit intense arm movements, but also regarding their positive reception and the consequent enjoyment.[76,77] Because the game designers try to maximise the likelihood that these games will be appealing and played for a large number of hours, and, consequently, commercially successful,[21] they are designed according to a number of well-researched principles. However, owing to the omission of medical considerations during development, and despite accommodative design for a diverse target audience, commercial game systems typically lack the levels of adaption needed to fit the heterogeneous nature of stroke-related dysfunctions,[43,78] making play, or even control of input devices, difficult and frustrating.[20] One possible solution is to re-purpose commercial games with more appropriate input devices, as has been attempted with *Fruit Ninja*[73,74] and *Tetris*.[79] A much more credible and prevalent solution, however, is the design of custom-made games and game systems, built to better accommodate patients' physical needs while concomitantly providing games which are designed by the same principles. This could be key in creating patients as engaged with rehabilitative games as 'hardcore gamers' are with the latest commercial games.

Game design concepts and their use in rehabilitation

Rizzo and Kim[23] suggested that "designers of rehabilitation tasks can benefit from examining the formulas that commercial game developers use in the creation of interactive computer games". Existing research in this area has been directed towards demonstrating that there is a scientific basis for what makes a successful video game and that design principles can be used as a framework for conceptualising engagement and motivation in gameplay. This may be even more relevant to games for stroke rehabilitation, as gameplay which is objectively engaging may increase compliance or distract the user from fatigue or pain.[80] While there has been some debate on the game design principles most salient in this area, there has been far less discussion on just *how* these principles have been implemented. A list of game design factors follows, constructed from a selection of research in this area, with information concerning how they have been used and applied in existing examples. These principles are also shown in Table 1, with brief summaries of how they feature in various commercial/custom solutions.

Meaningful play and feedback

'Meaningful play' emerges from the relationship between player action and system outcome, apparent to the player through feedback.[81] This interaction between the player and procedures of the game system is what primarily shapes the player's experience,[42] and the goal of successful game design is the creation of meaningful play.[82] Playing a game means making choices and taking actions, with every action taken resulting in a change affecting the overall game system.[83] The principles of an 'action plan' to perform a specific movement[84] and the anticipation of feedback and outcomes as a result may also be critical to motor learning.[85] For play to become meaningful and for the continued incentive to keep playing, the player must be able to perceive not only the immediate result of their action, but also how the outcome of the action was integrated into the larger context of the game.[82] Several examples have cited this concept as an important aspect in the creation of games for stroke rehabilitation.[86,87]

The concept of feedback is paramount in creating and maintaining meaningful play, since feedback is how a player perceives the results of their actions.[88] Without a quantifiable advantage/disadvantage for performing an action successfully/unsuccessfully, the experience will be less engaging.[89] It is important in rehabilitation also, as increased levels of feedback, whether graded (degree) or absolute (correct/incorrect),[90] can lead to increased training effects and enhance motor learning.[91] Positive feedback (correct performance) can enhance motivation, self-efficacy and compliance, while negative feedback (incorrect performance) can facilitate skill improvement.[92,93] Lack of negative feedback can lead to frustration, such as in the case of the Ammi Interactive Rehabilitation Touch games *Memory* and *Puzzle*,[94] where players were left confused as to why their actions were not yielding positive in-game outcomes. As well as showing the players the immediate results of their actions,[95] such as trace and aura effects in the tangible user interface system *Elements*,[96] progress identifiers such as an on-screen score can assist in demonstrating progress towards objectives.[97] A person's own sensory-perceptual information, available as a result of their actions, is known as intrinsic feedback[92,98] and can be mediated through vision (text, icons, scores), audition (sound effects, dialogue), or touch (haptic feedback, pressure, vibration). Advanced touch feedback was demonstrated with a collection of custom Kinect games played with a haptic glove,[99] which activated various palm- and finger-situated vibration motors to produce real-time vibration patterns based on the virtual interaction. During gameplay in rehabilitation, intrinsic feedback is often supplemented by extrinsic or augmented feedback, which can include verbal encouragement, points, charts, or a video replay. This can prove beneficial if cognitive impairments prevent appropriate transmission of intrinsic elements[98,100] and may also enhance control, motivation, retention and transfer, if delivered at the patient's own pace.[101] Indeed, the use of extrinsic feedback is advocated in much of the literature, categorised as either Knowledge of Performance (KP) or Knowledge of Results (KR). KP refers to the movement characteristics which lead to the performance outcome, while KR refers to the outcome of performing a skill or achieving a goal.[93] There is evidence to suggest that the use of KP during repetitive movement practice results in better motor outcomes than the use of KR, as the latter can discourage variety in learning strategies (e.g. active problem-solving activities) and can lead to feedback dependency.[92] Furthermore, feedback that is prescriptive rather than descriptive can make use of the brain's declarative learning process, resulting in factual knowledge that can be recalled from one's long-term memory.[102] A system that garnered the use of both KP and KR was the Gertner Tele-Motion Rehab system,[103] which provided feedback about the quality

Table 1. Examples of how game design principles exist in various custom and commercial games/game systems.

	Game/Game system	Feedback	Goals	Rewards	Challenge	Difficulty
Custom	*Circus Challenge*	Visual feedback via animated characters completing actions which mimic the user's movements.	Particular goals (e.g. achieve a total score of 3000 before Tuesday) are shown in terms of percentage achieved.	Up to three stars are rewarded per level per mini-game, depending on performance.	Assessment Game provides in-game assessment to a clinical standard so that targets can be set accordingly.	Two-handed tasks with increasing levels of movement complexity and coordination.
	Message-in-a-Bottle system	Visual, aural and haptic feedback transmitted in case defects in one prevent understanding.	Combination of short- (catching bottle, answering questions), medium- (progressing through areas) and long-term (finding the treasuring) goals.	Collecting points through success progresses the game, rewarding the player with new areas of the island.	Combination of motor and cognitive challenges and HapticMaster can autonomously assist with motor challenges, if needed.	Eight difficulty levels automatically adapted to be contingent on task performance and biomechanics.
	RehabMaster	An on-screen version of the user while mimicking avatar movements grants instant visual feedback.	In-game goals linked to real-world goals with after-session video playbacks of user's performance to show progress.	Ability to play against other patients and beat scores offers rewards of glory.	Level of challenge configured before play by an occupational therapist.	Difficulty of the game can be adapted as and when needed by the presiding occupational therapist.
	University of Ulster games	Player could see their own hand and its interaction with virtual objects in *Brick-a-Break* and *Shelf Stack*.	Gameplay involving stacking objects on shelves relates to real-world goals in *Shelf Stack*.	Unlockable levels with harder challenges if enough points are accumulated in *Whack-a-Mouse*.	An initial calibration task tested ROM in eight directions to set an appropriate level of challenge in *Arrow Attack* and *Bubble Trouble*.	Length of appearance time and locus of mice dependent on performance data and level progression in *Whack-a-Mouse*.
Commercial	*EyeToy: Play* (Sony)	Player is displayed on screen while interacting with virtual objects, increasing immersion through instant visual feedback.	Goal of each mini-game is to get a high score and beat previous records.	Depending on points gained, a bonus round offers the chance to earn more bonus points in *Kung Foo*.	Multiplayer option to play against other people and compete for the best score.	Predetermined difficulty (easy, medium, hard) selectable before start of mini-game.
	Fruit Ninja (Halfbrick Studios)	Instant visual feedback granted via a knife trail which is left by finger swipes.	In arcade mode, the player's goal is to get the most points possible in 1 minute. Bonus points are awarded for specific achievements.	New blades and backgrounds can be unlocked as awards and achievements are accumulated.	Different moves available to suit different modes of play and different skills levels/abilities.	Difficulty increases over time as both more fruit and more bombs appear.
	Kinect Adventures! (Good Science Studio)	Avatar in the game world mimics the player's full body movements, increasing immersion through instant visual feedback.	Main goal is to collect 'adventure pins' to earn medals and progress through the game.	Bronze, silver, gold and platinum medals can be earned which progress the player through the story mode.	Depending on number of medals earned, games make it harder to earn 'adventure pins', even on easiest levels.	Multiple levels of each game with slightly different (harder) objectives, e.g. more leaks to plug simultaneously in *20,000 Leaks*.
	Wii Sports (Nintendo)	Controller vibrates granting haptic feedback. Crowds grow according to the player's skill level in *Tennis* and *Boxing*.	The inclusion of skill points (which can be won by winning events) and levels gives players the goal to advance by playing more.	Bronze, silver, gold and platinum medals can be earned depending on high scores for each mini-game in training mode.	Games can be played against the computer or against other players.	Difficulty of computer opponents depends on skill level of current player to avoid the game being too hard or too easy.

of upper limb motion and compensatory movements (KP), including both descriptive online data and prescriptive remote contact with a clinician, as well as ongoing feedback on the game progress and scores (KR).

Goals and rewards

Goals in games can range from short-term, typically quick navigational beacons designed to provide a constant source of satisfaction,[82] to long-term, more high-level, overriding objectives.[104] Low-level goals are usually bolstered by others which may take many play sessions and improvement in skill to achieve.[105] *Circus Challenge* (Limbs Alive), for instance, incorporates 100 separate upper limb actions into multiple difficulty levels over 10 game scenarios, including knife throwing and juggling.[106] While the short-term goal may be to achieve a 3-star rating on each of the current difficulties for each mini-game, the long-term goal would be to achieve 3-star ratings on every difficulty level for every mini-game, thereby achieving maximum scores for all 100 movements. The accumulation of these goals is a powerful means in order to get the player invested and involved[81] and can inspire participants to perform tasks for personal gain or satisfaction via incentives and rewards,[107,108] as well as helping cultivate meaningful play by allowing the significance of an action to be understood in terms of progress towards winning the game.[82] Goals and clear instructions have been found to increase motivation,[46] while a lack of goals and instructions can result in confusion and frustration.[45] Goal-directed movements, either in-game or out, are essential for stroke rehabilitation,[11,15,16] particularly 'concrete' goals, which focus upon physical interactions with objects or persons.[100] The virtual re-imagination of real-world activities, such as supermarket shopping[109] and posting an envelope[110] have been incorporated into game-based rehabilitation. In addition, hammering a nail and pouring a glass into a carafe are central gameplay aspects of the VRRS system from Italy, which yielded increased Fugl-Meyer Assessment and Functional Independence Measure scores in a 376-patient study.[111]

Game rewards have been categorised by various researchers. Hallford et al.[112] claimed rewards to be either of glory, sustenance, access or facility, while Bateman[113] further categorised them as either currency, rank, mechanical, narrative, emotional, new toys, new places, completeness, or victory. The type of reward attained from the achievement of a goal, while different across game genres, is even more different with regards to what is desirable for different players. There is no way of elucidating an ideal reward for any one player, whether healthy or recovering from stroke, as this relates to the player's 'player type',[114] the reward's form/characteristics and how the player wishes to utilise it.[115] However, this mentioned, all gameplay is motivated by rewarding experiences.[21] While rewards in games traditionally come from level progression or goal attainment,[116] games for rehabilitation should reward engagement and effort over success.[39] The intrinsic/extrinsic motivation to receive particular personal, competitive or material rewards has also been discussed in research.[117] One of the main systems of reward in rehabilitative games is a difficulty level/star system. The Elinor gaming system,[118] for instance, allowed players to earn performance-contingent stars for each level before moving on. If the player failed a level five consecutive times, they were returned to the former level to ensure that reaching the limit of their ability did not prevent ongoing achievement. Recently, research has given insight into the neuroscience of reward and motivation. Activity in the nucleus accumbens, the area of the brain associated with the pursuit of rewards and pleasure,[119] has been found to scale linearly to the probability of receiving a reward,[120] as well as the release of dopamine, associated with reward-based learning, feelings of pleasure/enjoyment and motivation to perform specific behaviours.[21,89] The properties of the dopaminergic reward system that underlies gameplay, however, may change as a function of disease or injury.[21] Psychological and physiological rewards such as these have been found to result from decision-making,[119] uncertainty[121] and exploration,[122] all factors inherent in video games.

Challenge and difficulty

Typically, games are designed to be playable by individuals with vastly different levels of motivation, experience, skill, and different play styles and strategic approaches.[123] Individuals left with heterogeneous cognitive/motor dysfunctions, however, require an even wider-ranging scope of difficulty.[124] For this reason, many games for rehabilitation, such as the Kinect-based *Jewel Thief*[125] and the Rutgers Arm[126] include pre-game calibration tasks to assess range of movement and then form the proceeding game parameters on these measurements. Despite precautions, failure is still a prominent concern and the risk may be more sizeable in rehabilitative games. Some games prevent explicit failure, such as a recent mirror-training game[127] which skipped over failed hand posture tasks to avoid detrimental feelings of inefficacy. However, it should be noted that failing can grant opportunities for satisfaction and proof of improvement when obstacles are overcome,[128] if handled in a positive way. Failing positively can increase excitement and eagerness to retry a task,[129] and even frustration can contribute to a pleasurable and cathartic experience.[123]

Game difficulty should begin low to match levels of ability and familiarity,[21] gradually increasing alongside player skill,[104,130] although this cannot be at a gradient ideal for everyone. Methods such as selecting easy, medium or hard play, or using increasingly difficult levels, are both prevalent forms of adaptable or predetermined difficulty, while in-game difficulty adjustment is adaptive or dynamic difficulty.[131] From a motor learning perspective, an optimal level of challenge and 'desirable difficulties' are important,[85,132] and the aim of in-game difficulty adjustment is to achieve a harmonious balance between challenge and skill. This is required to achieve a state of flow,[133] the psychological description of energised focus, full immersion, involvement and enjoyment.[134] Flow is important in the realms of rehabilitation, as an activity will be deemed rewarding if an individual can use their sensory and physical potential in a novel/challenging way.[135] The theory has been applied extensively to games too, particularly with *GameFlow*,[95] a contemporary manifestation, outlining core elements of player enjoyment. Autonomous adjustment of difficulty contingent on current performance and success, via heuristic observations for example, can keep the player in a state of flow by increasing the challenge when the game appears too easy and decreasing it when it appears too hard,[136] helping to avoid anxiety or boredom.[137] Furthermore, maintaining the balance and extending the time between a player losing or winning is greatly advantageous for maximising potential for functional improvements. Intelligent control of difficulty was achieved on the Rehabilitation Gaming System (RGS) by the *Personalised Training Module*[138] and the *Intelligent Game Engine for Rehabilitation*, used with a Kinect *Fruit Catcher* game,[139] to name two examples. Autonomous control was achieved in earnest by the Adaptive Mixed Reality Rehabilitation System's *Adaptive Therapy Sequence*, which guided the patient through an entire rehabilitation session, depending upon their performance and kinematic improvements.[140]

Custom systems

Many custom game systems have used game design principles extensively to influence their development, although very few have cited these in detail. A system that did highlight a particular affinity for design, according to these principles, was the RehabMaster™ (D-Gate, Seoul, Korea), a gesture-based system played with upper limb and trunk movements while seated opposite a large monitor.[87] Four games were designed that not only used goal-directed movements inspired by the Fugl-Meyer Assessment, Action Research Arm Test and Motricity Index, but were also bolstered by knowledge of meaningful play and an optimal level of challenge to try and inspire maximum enjoyment, immersion and intrinsic motivation. Three user groups were involved in designing the RehabMaster – stroke patients, occupational therapists and physiatrists – showing that, far from being supplementary or a novelty, the development and use of game systems such as this may represent the successful collaboration of industry, design, research and health care.[23] The considerations for all stakeholders associated with a patient's care within a multidisciplinary approach is important, as focus on the patient alone could compromise the success of the technology.[39] In the games *Underwater Fire*, *Goalkeeper* and *Bughunter*, the speed, size and trajectory of the objects was controllable and adaptable depending on current levels of success or failure, similar to the game *Spheroids* on the aforementioned RGS.[138] Unlike some systems, however, an occupational therapist sat next to the monitor, having access to real-time performance data and controlling the difficulty. They could also provide extrinsic feedback and physical assistance. A training feature and the fourth game *Rollercoaster* both tasked the patient with mimicking the positions and movements of an on-screen avatar as accurately as possible,[141] promoting bilateral movement and mirror training. The use of the RehabMaster was found to result in functional improvements in both chronic and acute/sub-acute stroke patients, with positive reports of skill development, improved immersion and motivation, when compared with conventional therapy.[87] In addition, improvements in health-related quality of life, particularly role limitation due to emotional problems and depression, were noted in another trial.[142] A usability test yielded results indicating improved attention and a 'flow experience' for the patients, characterised by control, attentional focus, intrinsic interest and curiosity, which may have minimised the drop-out rate.[87] The highly realistic and immersive environment may have helped facilitate a sense of presence,[143] which may have a positive correlation with task performance.[144]

The *Message-in-a-Bottle* (MIB) game[145] was played on a large projector screen using a HapticMaster (Moog FCS) robotic device. Research undertaken which inspired the design of the MIB system alluded to the importance of realism (realistic setting, sound and graphics), customisation, rapid absorption rate, winning and losing and a variety of control options,[146] while objectives requiring higher-order thinking skills and creative problem solving[147] were also deemed significant. In MIB, the player is presented with highly realistic views of a tropical island and tasked with using the haptic device to pick up virtual bottles that float towards him/her, the size, weight and speed of which can be altered according to the individual's ability. After this initial physical task, the message in the bottle presents one of an available 300 questions, split over nine categories, before asking the user to place the bottle in one of two virtual baskets, according to which answer he/she thinks is correct. The combination of both motor and cognitive challenges is perhaps the most important feature of the MIB. Later levels require more difficult motor tasks, and eight motor difficulty levels are stepped through according to the continual observation of task performance and biomechanics. As well as attempting to focus the resultant game on principles of good game design, the system was created with the objective of increasing levels of intrinsic motivation. An Intrinsic Motivation Inventory questionnaire demonstrated the system's success in this area, motivating players to play for more beneficial amounts of time.

Extensive work has been undertaken in this field over the last decade by James Burke and his colleagues at the University of Ulster, Northern Ireland. Game design principles, particularly the ideas behind challenge, handling failure and meaningful play, were extensively explored and integrated into a number of custom-made games.[51,148] Sensor-based games included *Fishing*, *Catch the Orange* and *Whack-a-Mouse*,[148] use of which contributed to improved functional measurements with eight stroke patients, after 10 sessions and also at a 6-week follow-up.[149] The latter, a 'Whack-a-Mole' style game, adapted both the length of time mice would appear out of the holes and the locus of them upon performance data and level progression. A dog was also added in later levels which needed to be avoided, adding elements of visual discrimination and problem solving. An increase in speed/difficulty was also a feature of the vision-based game *Rabbit Chase*[150] and deemed an important factor for overall enjoyment.[148] For *Rabbit Chase*, *Arrow Attack* and *Bubble Trouble*, an initial calibration task tested the reach ability of the patient in eight directions.[51] These games were designed to include specific features which could combat certain afflictions; for example, time limits and direct feedback were used to combat coordination/timing problems.[151] *Brick'a'Break* and *Shelf Stack* were a pair of augmented reality games developed to satisfy the ability to customise the tasks and handle failure positively/conservatively.[86] For *Shelf Stack*, the player was encouraged to simply increase their score over play sessions, so they essentially could not fail. In *Brick'a'Break*, there was no time limit (unlike the popular game *Breakout* on which it was based) and only a short pause when the ball was missed (without any further penalties) in order to avoid discouragement from playing.

Towards a model for structured design

A collection of research exists which has elucidated core game design principles that could be useful in stroke rehabilitation, while also aiming to move the collaborative efforts of designers and therapists towards a model for the structured design of such games. Features which have been advocated by this research for inclusion in such games are summarised in Table 2. According to this summary, socialisation is the most important aspect, followed by motivational feedback, appropriate cognitive challenge, adaptable difficulty, challenge and a simple interface. In attempting to build a framework for game environment design, Flores et al.[152] attempted to outline which features of games make them better or less suited for motor rehabilitation. The taxonomy comprised two sets of criteria: stroke rehabilitation and elderly entertainment. The authors postulated that the ideal game for UE stroke rehabilitation would satisfy all criteria from both sets. Indeed, both *Computer Chess* and *Whack-a-Mouse*[51,148] were analysed using this taxonomy. *Computer Chess* satisfied 100% of elderly entertainment points but only 20% of stroke rehabilitation points, while *Whack-a-Mouse* satisfied 50% of elderly entertainment points yet 80% of stroke rehabilitation points. The elements for 'stroke rehabilitation' included an adaptability to motor skill level, demonstrated extensively in games which feature automatic difficulty adjustment[87,138,139,153] and therapy-appropriate range of motion, a factor in examples using pre-game calibration tasks.[51,126,153,154] In addition, appropriate feedback and meaningful tasks, such as the reach, grasp, push and pull movements used with a virtual glove[41] were included, as well as a focus diverted from exercise, a concept which the University of Illinois' Art-empowered VR project featured heavily, guiding the player through a virtual story-like *Alice in Wonderland* experience.[155] Intentional movement and quantitative measurement were also later added, alongside various other user-centred elements.[39]

Prominent features of a system for 'elderly entertainment' included such well-known factors as motivational feedback, the creation of new learning experiences and social activity. A simple objective/interface, like the toned down colours and sounds of the Elinor system[118] to avoid cognitive overload and fatigue, was deemed as important and, additionally, presenting a sensitivity to decreased sensory acuity and slower responses, particularly important for individuals who are either elderly or suffering from cognitive impairments. An extreme example of this would be the vision-based system from Hadassah University Hospital, Israel, which replaced the impaired limb

Table 2. Proposed features of importance when designing game systems for stroke rehabilitation according to published survey papers, taxonomies and frameworks.

Suggested feature of stroke rehabilitation game system	Alankus[161]	Burke[51,149,151]	Flores[153]	GAMER[162]	Goude[152]	Lohse[21]	Perry[39]	Rego[160]	Total
Actions/movements focused to combat specific problems					×				1
Adaptability to motor skill level (difficulty)			×	×			×	×	4
Appropriate cognitive challenge	×		×	×				×	4
Appropriateness of genre			×					×	2
Challenge		×		×		×	×		4
Choice/interactivity						×			1
Clear instructions						×			1
Creation of new learning experiences			×						1
Data logging/progress monitoring				×			×	×	3
Focus diverted from exercise			×						1
Focus on coordination				×	×				2
Goals and targets				×					1
Handling failure appropriately		×		×					2
Immersion					×				1
Intentional movement							×		1
Meaningful play		×		×					2
Meaningful tasks			×	×					2
Motivational feedback			×	×		×	×	×	5
Portability				×				×	2
Quantitative measurement							×		1
Quick games					×				1
Rewards				×		×			2
Sensitivity to decreased sensory acuity/slower responses			×	×			×		3
Simple interface			×	×			×	×	4
Smooth learning curves					×				1
Socialisation	×		×	×		×	×	×	6
Therapy-appropriate range of motion	×		×						2
Time limits					×				1

with a virtual representation and accentuated the user's limited movements into amplified full-range movements, thus promoting recovery.[156] Appropriateness of genre was also deemed an important factor, and many systems have used reimagined versions of popular game concepts such as *Pong*,[157] *Tennis*,[118] *Breakout*,[86] *Guitar Hero*[158] and *Snake*.[118,127] The most popular games out of the 15 included on the Elinor system were proven to be based on well-established games.[118] Genre was also an element of another taxonomy by Rego et al.,[159] which was recommended for the analytical comparison and determination of serious games for rehabilitation, but could also be applied to the design too.

The last element of 'elderly entertainment' was appropriate cognitive challenge, an element mentioned by other research in this area,[160,161] particularly in relation to the learning outcomes achievable from engaging cognitive mechanisms.[22] Cognitive elements in games for stroke rehabilitation are included to either break the monotony of repetitive movements,[145] to evoke timed responses, hand-to-eye co-ordination[161] or, finally, to inspire short-term visual and memory challenges, such as the Rutgers Arm *Card Island* game.[162] Furthermore, integrating varied problem solving may be a powerful pedagogical tool, helping also develop high-order thinking skills.[163] Cognitive challenge was one of three key attributes outlined by Alankus et al.,[160] in addition to social context and motion type, as a prerequisite to the design of nine stroke rehabilitation games, incorporating differentiating input methods, cognitive challenges and competitive/collaborative elements. Motivation was outlined as an important factor, and the use of both therapist-determined difficulty and automatic difficulty adjustment were advocated, as well as the inclusion of non-player characters and storylines. Several of these findings have alluded to the concept of socialisation[152,159] and, indeed, the ability to play these games with or against other players seems to be beneficial for motivation, engagement, learning and may be central to player enjoyment.[164] Sociality was also an aspect of a recent and exhaustive investigation into the advantages of design principles in physical therapy.[21]

During the creation of the 3D VR Activity Station at the University of Göteborg,[165] Goude et al.[151] mapped specific and common post-stroke motor impairments against various game design principles and features.[108] Focusing on the techniques used to combat certain impairment, precise game features were postulated to be of benefit, if included, to the correlative dysfunction. For example, rhythm-based actions could be used to combat timing problems associated with discoordination, and precise manoeuvring and dexterity-based actions could be used to diminish scaling/proprioception-related problems. Only a subset of the taxonomy was published, but the development of the 15 games which came pre-loaded on the 3D VR Activity Station were influenced by this research. This work was also cited in the creation of several vision-based serious games at the University of Ulster,[51,148,150] and Burke's work in this area (previously mentioned) presents a very functional example of how existing research into game principles can be utilised in the creation of custom-made games. Resulting from the extensive work at the University of Ulster, a vast framework called the *GAMER* framework was recently presented by Charles and McDonough.[161] *GAMER* categorises components relating to the player, primarily their therapeutic goals in terms of transferability to ADL, coordination, extremity focus, cognition and movements, and components relating to the interface, such as the input, output, deployment and ability to data log and the audio and visual consistency in the design of the user interface itself. Components relating to the game itself are the most exhaustive, comprising elements such as varied, easy to learn/play game content, concepts of meaningful play comprised of feedback, goals and targets and play rewards and, finally, challenge, comprised of appropriate difficulty, failure and competition.

Conclusion

This article has demonstrated how game theory can and has been applied to the creation of games for upper limb stroke rehabilitation. Low motivation and engagement with physical therapy are very real and prominent concerns,[166] but encouraging evidence has shown that games can be a powerful therapeutic tool when intelligently integrated into rehabilitation and can help combat these problems.[23,24,29,77] In addition to improving compliance, games can also fulfil principles of motor learning[22] and induce/modulate neuroplastic adaptations in the brain.[26] Both commercial and custom-made game systems have been re-purposed/developed for use in upper limb stroke rehabilitation, although where one type seems to excel, the other suffers and vice versa. This article includes a brief and recent history of commercial interventions in this area, although their efficacy, accessibility and cost-effectiveness must be offset against the adaptive and sometimes improvisational nature of their application. Their detriments seem to support the case for custom-made interventions.

The creation of a video game is a complex and multifaceted process, and the gold standard for their modern design is the result of over half a century of painstaking research and exhaustive development. As a result of an extensive literature survey, a number of core factors of game design were distilled and discussed in detail: meaningful play, feedback, goals, rewards, challenge, difficulty, failure and flow. These factors could be as integral to the creation of custom-made games for stroke rehabilitation as they are to the creation of commercial games for the general public, particularly if these aspects, which scientifically contribute to motivation, engagement and commercial success, are combined with technologically advanced control systems that compensate for motor impairment. The increasing success of the games industry is a testament to the ability of such design factors to maximise engagement and create meaningful, addictive experiences for players, although research on these factors in the area of stroke rehabilitation is relatively limited. As a result, few custom-made games cite these principles in their body of research, but those which do have been presented and discussed in this article.

The so far limited research elucidating these game design concepts and advocating their utilisation in stroke rehabilitation has also been presented, and this evidence in particular helps draw a salient and inextricable link between the two fields. Further work is needed, however, to cement the two fields together and further highlight the importance of the relationship between the motor/cognitive outcomes achievable from the design principles, to the most important aspect of the entire area: the stroke survivor. Further work is also needed to empirically demonstrate the significant advantages of using video games in therapy. While they appear to have much promise, evidence associated with the application of commercial games is typically considered low quality due to small participant numbers, inconsistent and poorly reported results,[24,77] plus an erroneous focus on time spent in therapy over the number of movement repetitions.[21] In addition, evidence associated with the application of custom-made games seems to suffer too, from data too small to draw strong conclusions but encouraging enough to support future exponential development.[30,76]

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References

1. Mackay J and Mensah GA. *The atlas of heart disease and stroke*. Geneva, Switzerland: World Health Organization, 2004.
2. Townsend N, Wickramasinghe K, Bhatnagar P, et al. *Coronary heart disease statistics 2012 edition*. London: British Heart Foundation, 2012, p.107.
3. Feys HM, De Weerdt WJ, Selz BE, et al. Effect of a therapeutic intervention for the hemiplegic upper limb in the acute phase after stroke a single-blind, randomized, controlled multicenter trial. *Stroke* 1998; 29: 785–792.
4. Sommerfeld DK, Eek EU, Svensson AK, et al. Spasticity after stroke: Its occurrence and association with motor impairments and activity limitations. *Stroke* 2004; 35: 134–139.
5. Kong K-H, Chua K and Lee J. Recovery of upper limb dexterity in patients more than 1 year after stroke: Frequency, clinical correlates and predictors. *NeuroRehabilitation* 2011; 28: 105–111.
6. Langhorne P, Bernhardt J and Kwakkel G. Stroke rehabilitation. *Lancet* 2011; 377: 1693–1702.
7. Newman M. The process of recovery: After hemiplegia. *Stroke* 1972; 3: 702–710.
8. O'Neil O, Gatzidis C and Swain I. A state of the art survey in the use of video games for upper limb stroke rehabilitation. In: *Virtual, Augmented Reality and Serious Games for Healthcare 1*. Springer, 2014, pp.345–370.
9. Intercollegiate Stroke Working Party. Public Report for England, Wales and Northern Ireland. *National Sentinel Stroke Clinical Audit 2010*. London: Royal College of Physicians, 2010.
10. McHugh G and Swain I. A comparison between reported and ideal patient-to-therapist ratios for stroke rehabilitation. *Health* 2013; 5: 105–112.
11. Stokes M and Stack E. *Physical management for neurological conditions*, 3rd ed. Edinburgh: Elsevier Health Sciences, 2011.
12. Hughes AM, Burridge JH, Demain SH, et al. Translation of evidence-based Assistive Technologies into stroke rehabilitation: Users' perceptions of the barriers and opportunities. *BMC Health Serv Res* 2014; 14: 1–12.
13. Demain S, Burridge J, Ellis-Hill C, et al. Assistive technologies after stroke: Self-management or fending for yourself? A focus group study. *BMC Health Serv Res* 2013; 13: 334.
14. Coupar F, Pollock A, Legg LA, et al. Home-based therapy programmes for upper limb functional recovery following stroke. *Cochrane Database Syst Rev* 2012; 5: CD006755.
15. Hubbard IJ, Parsons MW, Neilson C, et al. Task-specific training: Evidence for and translation to clinical practice. *Occup Ther Int* 2009; 16: 175–189.
16. Veerbeek JM, van Wegen E, van Peppen R, et al. What is the evidence for physical therapy poststroke? A systematic review and meta-analysis. *PloS One* 2014; 9: e87987.
17. Richards LG, Stewart KC, Woodbury ML, et al. Movement-dependent stroke recovery: A systematic review and meta-analysis of TMS and fMRI evidence. *Neuropsychologia* 2008; 46: 3–11.
18. Wolf SL. Revisiting constraint-induced movement therapy: are we too smitten with the mitten? Is all nonuse "learned"? and other quandaries. *Phys Ther* 2007; 87: 1212–1223.
19. Whitall J, Waller SM, Sorkin JD, et al. Bilateral and unilateral arm training improve motor function through differing neuroplastic mechanisms: A single-blinded randomized controlled trial. *Neurorehabil Neural Repair* 2011; 25: 118–129.
20. Burdea G. Keynote address: Virtual rehabilitation-benefits and challenges. *1st International Workshop on Virtual Reality Rehabilitation (Mental Health, Neurological, Physical, Vocational) VRMHR*. sn, 2002, pp.1–11.
21. Lohse K, Shirzad N, Verster A, et al. Video games and rehabilitation: Using design principles to enhance engagement in physical therapy. *J Neurol Phys Ther* 2013; 37: 166–175.
22. Levin MF, Weiss PL and Keshner EA. Emergence of virtual reality as a tool for upper limb rehabilitation:

Incorporation of motor control and motor learning principles. *Phys Ther* 2015; 95: 415–425.
23. Rizzo A and Kim GJ. A SWOT analysis of the field of virtual reality rehabilitation and therapy. *Presence* 2005; 14: 119–146.
24. Laver KE, George S, Thomas S, et al. Virtual reality for stroke rehabilitation. *Eur J Phys Rehab Med* 2015; 51: 497–506.
25. Reinthal A, Szirony K, Clark C, et al. ENGAGE: Guided activity-based gaming in neurorehabilitation after stroke: A pilot study. *Stroke Res Treat* 2012; 2012: 784232.
26. Orihuela-Espina F, Fernandez del Castillo I, Palafox L, et al. Neural reorganization accompanying upper limb motor rehabilitation from stroke with virtual reality-based gesture therapy. *Top Stroke Rehabil* 2013; 20: 197–209.
27. Schaechter JD. Motor rehabilitation and brain plasticity after hemiparetic stroke. *Prog Neurobiol* 2004; 73: 61–72.
28. Kleim JA and Jones TA. Principles of experience-dependent neural plasticity: Implications for rehabilitation after brain damage. *J Speech Lang Hear Res* 2008; 51: S225–S239.
29. Lange B, Koenig S, Chang C-Y, et al. Designing informed game-based rehabilitation tasks leveraging advances in virtual reality. *Disabil Rehabil* 2012; 34: 1863–1870.
30. Henderson A, Korner-Bitensky N and Levin M. Virtual reality in stroke rehabilitation: A systematic review of its effectiveness for upper limb motor recovery. *Top Stroke Rehabil* 2007; 14: 52–61.
31. Interactive Advertising Bureau. *Gaming Britain: A nation united by digital play*. London: Interactive Advertising Bureau, 2011.
32. Schmidt RA and Lee TD. *Motor control and learning: A behavioral emphasis*, 3rd ed. Champaign, IL, US: Human Kinetics Publishers, 1999.
33. West C, Bowen A, Hesketh A, et al. Interventions for motor apraxia following stroke. *Cochrane Database Syst Rev* 2008; 1: CD004132.
34. Pomeroy V, Aglioti SM, Mark VW, et al. Neurological principles and rehabilitation of action disorders rehabilitation interventions. *Neurorehabil Neural Repair* 2011; 25: 33S–43S.
35. Plautz EJ, Milliken GW and Nudo RJ. Effects of repetitive motor training on movement representations in adult squirrel monkeys: Role of use versus learning. *Neurobiol Learn Mem* 2000; 74: 27–55.
36. Adamovich SV, Fluet GG, Tunik E, et al. Sensorimotor training in virtual reality: A review. *Neurorehabilitation* 2009; 25: 29.
37. Egglestone SR, Axelrod L, Nind T, et al. A design framework for a home-based stroke rehabilitation system: Identifying the key components. *2009 3rd International Conference on Pervasive Computing Technologies for Healthcare - Pervasive Health 2009, PCTHealth 2009*. 2009.
38. Lang CE, MacDonald JR and Gnip C. Counting repetitions: an observational study of outpatient therapy for people with hemiparesis post-stroke. *J Neurol Phys Ther* 2007; 31: 3–10.
39. Perry JC, Andureu J, Cavallaro FI, et al. Effective game use in neurorehabilitation: User-centered perspectives. In: *Handbook of research on improving learning and motivation through educational games*. IGI Global, 2010.
40. Michael DR and Chen SL. *Serious games: Games that educate, train, and inform*. Muska & Lipman/Premier-Trade, 2005.
41. Standen PJ, Brown DJ, Battersby S, et al. A study to evaluate a low cost virtual reality system for home based rehabilitation of the upper limb following stroke. *Int J Disabil Human Dev* 2011; 10: 337–341.
42. Bogost I. *Persuasive games: The expressive power of videogames*. Cambridge, MA: MIT Press, 2007.
43. Ortiz-Catalan M, Nijenhuis S, Ambrosch K, et al. Virtual Reality. In: *Emerging therapies in neurorehabilitation*. Springer, 2014, pp.249–265.
44. Proffitt R and Lange B. Considerations in the efficacy and effectiveness of virtual reality interventions for stroke rehabilitation: Moving the field forward. *Phys Ther* 2015; 95: 441–448.
45. Maclean N, Pound P, Wolfe C, et al. Qualitative analysis of stroke patients' motivation for rehabilitation. *BMJ* 2000; 321: 1051–1054.
46. Guthrie S and Harvey A. Motivation and its influence on outcome in rehabilitation. *Rev Clin Gerontol* 1994; 4: 235–243.
47. Ryan RM and Deci EL. Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *Am Psychol* 2000; 55: 68.
48. Ryan RM, Rigby CS and Przybylski A. The motivational pull of video games: A self-determination theory approach. *Motivat Emot* 2006; 30: 344–360.
49. Lloyd-Jones D, Adams RJ, Brown TM, et al. Executive summary: Heart disease and stroke statistics-2010 update: A report from the American Heart Association. *Circulation* 2010; 121: e46–e215.
50. Piron L, Turolla A, Tonin P, et al. Satisfaction with care in post-stroke patients undergoing a telerehabilitation programme at home. *J Telemed Telecare* 2008; 14: 257–260.
51. Burke JW, McNeill M, Charles DK, et al. Optimising engagement for stroke rehabilitation using serious games. *Visual Comput* 2009; 25: 1085–1099.
52. Gatica-Rojas V and Méndez-Rebolledo G. Virtual reality interface devices in the reorganization of neural networks in the brain of patients with neurological diseases. *Neural Regen Res* 2014; 9: 888.
53. Wingham J, Adie K, Turner D, et al. Participant and caregiver experience of the Nintendo Wii SportsTM after stroke: Qualitative study of the trial of Wii in stroke (TWIST). *Clin Rehabil* 2014; 29: 295–305.
54. Joo LY, Yin TS, Xu D, et al. A feasibility study using interactive commercial off-the-shelf computer gaming in upper limb rehabilitation in patients after stroke. *J Rehabil Med* 2010; 42: 437–441.
55. Saposnik G, Teasell R, Mamdani M, et al. Effectiveness of virtual reality using Wii gaming technology in stroke

rehabilitation a pilot randomized clinical trial and proof of principle. *Stroke* 2010; 41: 1477–1484.
56. Brosnan S. The potential of Wii-rehabilitation for persons recovering from acute stroke. *Phys Disabil* 2009; 32: 1–3.
57. Christie L, Kennedy S, Brennan B, et al. Does stroke Wii HAB work? Use of the Nintendo Wii for upper limb rehabilitation following stroke. *Cerebrovasc Dis* 2010; 29: 254–255.
58. Mouawad MR, Doust CG, Max MD, et al. Wii-based movement therapy to promote improved upper extremity function post-stroke: A pilot study. *J Rehabil Med* 2011; 43: 527–533.
59. Celinder D and Peoples H. Stroke patients' experiences with Wii Sports® during inpatient rehabilitation. *Scand J Occup Ther* 2012; 19: 457–463.
60. Lange B, Flynn S and Rizzo A. Initial usability assessment of off-the-shelf video game consoles for clinical game-based motor rehabilitation. *Phys Ther Rev* 2009; 14: 355–363.
61. Neil A, Ens S, Pelletier R, et al. Sony PlayStation EyeToy elicits higher levels of movement than the Nintendo Wii: Implications for stroke rehabilitation. *Eur J Phys Rehabil Med* 2013; 49: 13–21.
62. Weiss PL, Sveistrup H, Rand D, et al. Video capture virtual reality: A decade of rehabilitation assessment and intervention. *Phys Ther Rev* 2009; 14: 307–321.
63. Yavuzer G, Senel A, Atay M, et al. "Playstation EyeToy games" improve upper extremity-related motor functioning in subacute stroke: A randomized controlled clinical trial. *Eur J Phys Rehabil Med* 2008; 44: 237–244.
64. Rand D, Kizony R and Weiss PTL. The Sony PlayStation II EyeToy: Low-cost virtual reality for use in rehabilitation. *J Neurol Phy Ther* 2008; 32: 155–163.
65. Weichert F, Bachmann D, Rudak B, et al. Analysis of the accuracy and robustness of the leap motion controller. *Sensors* 2013; 13: 6380–6393.
66. Tanaka K, Parker J, Baradoy G, et al. A comparison of exergaming interfaces for use in rehabilitation programs and research. *Loading* 2012; 6: 69–81.
67. Webster D and Celik O. Systematic review of Kinect applications in elderly care and stroke rehabilitation. *J Neuroeng Rehabil* 2014; 11: 108.
68. Lee G. Effects of training using video games on the muscle strength, muscle tone, and activities of daily living of chronic stroke patients. *J Phys Ther Sci* 2013; 25: 595.
69. Guna J, Jakus G, Pogačnik M, et al. An analysis of the precision and reliability of the leap motion sensor and its suitability for static and dynamic tracking. *Sensors* 2014; 14: 3702–3720.
70. Calle J, Martínez P, Del Valle D, et al. Towards the achievement of natural interaction. In: *Engineering the user interface*. Springer, 2009, pp.1–19.
71. McCasker T. Fruit Ninja: How the slice-and-dice game reached 1bn downloads. *The Guardian* 2015.
72. Bao X, Mao Y, Lin Q, et al. Mechanism of Kinect-based virtual reality training for motor functional recovery of upper limbs after subacute stroke. *Neural Regen Res* 2013; 8: 2904.
73. Khademi M, Mousavi Hondori H, et al. Free-hand interaction with leap motion controller for stroke rehabilitation. *CHI'14 Extended Abstracts on Human Factors in Computing Systems*. ACM, 2014, pp.1663–1668.
74. Iosa M, Morone G, Fusco A, et al. Leap motion controlled videogame-based therapy for rehabilitation of elderly patients with subacute stroke: A feasibility pilot study. *Top Stroke Rehabil* 2015; 22: 306–316.
75. Charles D, Pedlow K, McDonough S, et al. Close range depth sensing cameras for virtual reality based hand rehabilitation. *J Assist Technol* 2014; 8: 138–149.
76. Lohse KR, Hilderman CG, Cheung KL, et al. Virtual reality therapy for adults post-stroke: A systematic review and meta-analysis exploring virtual environments and commercial games in therapy. *PloS One* 2014; 9: e93318.
77. Casserly DM and Baer GD. Effectiveness of commercially available gaming devices in upper limb stroke rehabilitation. *Phys Ther Rev* 2014; 19: 15–23.
78. Taylor MJ, McCormick D, Impson R, et al. Activity promoting gaming systems in exercise and rehabilitation. *J Rehabil Res Dev* 2011; 48: 1171–1186.
79. Kizony R, Weiss PLT, Shahar M, et al. TheraGame: A home based virtual reality rehabilitation system. *Int J Disabil Human Dev* 2006; 5: 265–270.
80. Primack BA, Carroll MV, McNamara M, et al. Role of video games in improving health-related outcomes: A systematic review. *Am J Prevent Med* 2012; 42: 630–638.
81. Church D. *Formal Abstract Design Tools*. Gamasutra, 1999.
82. Salen K and Zimmerman E. *Rules of play: Game design fundamentals*. Cambridge, MA: MIT Press, 2004.
83. Zimmerman E. *How I Teach Game Design. (Lesson 2: Broken games and meaningful play)*. Gamasutra, 2014.
84. Miller GA, Galanter E and Pribram KH. *Plans and the structure of behavior*. New York: Holt, Rinehart and Winston. Inc, 1960.
85. Guadagnoli MA and Lee TD. Challenge point: A framework for conceptualizing the effects of various practice conditions in motor learning. *J Motor Behav* 2004; 36: 212–224.
86. Burke JW, McNeill M, Charles D, et al. Augmented reality games for upper-limb stroke rehabilitation. *Games and Virtual Worlds for Serious Applications (VS-GAMES), 2010 Second International Conference on*. IEEE, 2010, pp.75–78.
87. Shin J-H, Ryu H and Jang SH. A task-specific interactive game-based virtual reality rehabilitation system for patients with stroke: A usability test and two clinical experiments. *J Neuroeng Rehabil* 2014; 11: 32.
88. Bates B. *Game design*, 2nd ed. Portland: Premier Press, 2004.
89. Koster R. *Theory of fun for game design*. O'Reilly Media, Inc., 2013.
90. Rizzo AA, Schultheis M, Kerns KA, et al. Analysis of assets for virtual reality applications in neuropsychology. *Neuropsychol Rehabil* 2004; 14: 207–239.
91. Krakauer JW. Motor learning: Its relevance to stroke recovery and neurorehabilitation. *Curr Opin Neurol* 2006; 19: 84–90.

92. Timmermans AAA, Seelen HAM, Willmann RD, et al. Technology-assisted training of arm-hand skills in stroke: Concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. *J Neuroeng Rehabil* 2009; 6: 1–18.
93. Magill RA. *Motor learning and control: concepts and applications*, 7th ed. New York: McGraw-Hill, 2003.
94. Annett M, Anderson F and Bischof WF. User perspectives on tabletop therapy. *Proceedings of the 9th International Conference on Disability, Virtual Reality & Associated Technologies* (Laval, France, 2012). Citeseer, 2012.
95. Sweetser P and Wyeth P. GameFlow: A model for evaluating player enjoyment in games. *Comput Entertain* 2005; 3: 3.
96. Mumford N, Duckworth J, Thomas PR, et al. Upper limb virtual rehabilitation for traumatic brain injury: Initial evaluation of the elements system. *Brain Inj* 2010; 24: 780–791.
97. Federoff MA. *Heuristics and Usability Guidelines for the Creation and Evaluation of Fun in Video Games*. Citeseer, 2002.
98. van Vliet P and Wulf G. Extrinsic feedback for motor learning after stroke: What is the evidence? *Disabil Rehabil* 2006; 28: 831–840.
99. Sadihov D, Migge B, Gassert R, et al. Prototype of a VR upper-limb rehabilitation system enhanced with motion-based tactile feedback. *World Haptics Conference (WHC), 2013*. IEEE, 2013, pp.449–454.
100. Carr JH and Shepherd RB. *Stroke Rehabilitation: Guidelines for Exercise and Training to Optimize Motor Skill*. Edinburgh: Butterworth-Heinemann Medical, 2003.
101. Wulf G. Self-controlled practice enhances motor learning: implications for physiotherapy. *Physiotherapy* 2007; 93: 96–101.
102. Vidoni ED and Boyd LA. Achieving enlightenment: What do we know about the implicit learning system and its interaction with explicit knowledge? *J Neurol Phys Ther* 2007; 31: 145–154.
103. Weiss P, Kizony R, Elion O, et al. Development and validation of tele-health system for stroke rehabilitation. *Proceedings of the International Conference on Disability, Virtual Reality and Associated Technologies, Laval, France*, 2012.
104. Pagulayan RJ, Keeker K, Wixon D, et al. User-centered design in games. In: Jacko JA and Sears A (eds) *the human-computer interaction handbook: Fundamentals, evolving techniques and emerging applications*. New Jersey: Lawrence Erlbaum Associates, 2003, pp.883–905.
105. Burke J. *Games for upper limb stroke rehabilitation*. Ulster: University of Ulster, 2011.
106. Serradilla J, Shi J, Cheng Y, et al. Automatic assessment of upper limb function during play of the action video game, circus challenge: Validity and sensitivity to change. *2014 IEEE 3rd International Conference on Serious Games and Applications for Health (SeGAH)*, IEEE, 2014, pp.1–7.
107. Schell J. *The art of game design: A book of lenses*. Burlington: Morgan Kaufmann, 2008.
108. Björk S and Holopainen J. *Patterns in game design (game development series)*. Hingham, MA: Charles River Media, 2004.
109. Yin CW, Sien NY, Ying LA, et al. Virtual reality for upper extremity rehabilitation in early stroke: A pilot randomized controlled trial. *Clin Rehabil* 2014; 28: 1107–1114.
110. Holden M, Todorov E, Callahan J, et al. Virtual environment training improves motor performance in two patients with stroke: Case report. *J Neurol Phys Ther* 1999; 23: 57–67.
111. Turolla A, Dam M, Ventura L, et al. Virtual reality for the rehabilitation of the upper limb motor function after stroke: A prospective controlled trial. *J Neuroeng Rehabil* 2013; 10: 85.
112. Hallford N, Hallford J and LaMothe A. *Swords and circuitry: A designer's guide to computer role-playing games*. Premier Press, Incorporated, 2001.
113. Bateman C. *Beyond game design: Nine steps toward creating better videogames*. Cengage Learning, 2009.
114. Bartle R. Hearts, clubs, diamonds, spades: players who suit MUDs. *Journal of MUD Research* 1996; 1.
115. Wang H and Sun C-T. Game reward systems: gaming experiences and social meanings. *Proceedings of DiGRA 2011 Conference: Think Design Play*. 2011, pp.1–12.
116. Rouse III R. *Game design: Theory and practice*. Jones & Bartlett Learning, 2010.
117. James B, Fletcher B and Wearn N. *Three corners of reward in computer games*. Available at: http://www.fdg2013.org/program/papers/short03_james_etal.pdf (2013).
118. Backlund P, Taylor A-SA, Engström H, et al. Games on prescription! Evaluation of the Elinor console for home-based stroke rehabilitation. *Transactions on edutainment IX*. Springer, 2013, pp.49–64.
119. Clark L, Lawrence AJ, Astley-Jones F, et al. Gambling near-misses enhance motivation to gamble and recruit win-related brain circuitry. *Neuron* 2009; 61: 481–490.
120. Abler B, Walter H, Erk S, et al. Prediction error as a linear function of reward probability is coded in human nucleus accumbens. *Neuroimage* 2006; 31: 790–795.
121. Mirenowicz J and Schultz W. Importance of unpredictability for reward responses in primate dopamine neurons. *J Neurophysiol* 1994; 72: 1024–1027.
122. Hyland B, Reynolds J, Hay J, et al. Firing modes of midbrain dopamine cells in the freely moving rat. *Neuroscience* 2002; 114: 475–492.
123. IJsselsteijn W, De Kort Y, Poels K, et al. Characterising and measuring user experiences in digital games. *International Conference on Advances in Computer Entertainment Technology*, 2007, p.27.
124. Lewis GN and Rosie JA. Virtual reality games for movement rehabilitation in neurological conditions: How do we meet the needs and expectations of the users? *Disab Rehabil* 2012; 34: 1880–1886.
125. Lange B, Chang C-Y, Suma E, et al. Development and evaluation of low cost game-based balance rehabilitation tool using the Microsoft Kinect sensor. *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE*. IEEE, 2011, pp.1831–1834.

126. Burdea GC, Cioi D, Martin J, Fensterheim D, et al. The Rutgers Arm II rehabilitation system—a feasibility study. *IEEE Trans Neural Syst Rehabil Eng* 2010; 18: 505–514.
127. Trojan J, Diers M, Fuchs X, et al. An augmented reality home-training system based on the mirror training and imagery approach. *Behav Res Methods* 2014; 46: 634–640.
128. Juul J. *The art of failure: An essay on the pain of playing video games*. Cambridge, MA: Mit Press, 2013.
129. Lazzaro N. *Why we play games: Four keys to more emotion without story*. xeodesign, 2004.
130. Katz A and Yates L. *Inside electronic game design*. Prima Communications, Inc., 1995.
131. Gilleade KM and Dix A. Using frustration in the design of adaptive videogames. *Proceedings of the 2004 ACM SIGCHI International Conference on Advances in Computer Entertainment Technology*. ACM, 2004, pp.228–232.
132. Björk EL and Björk RA. Making things hard on yourself, but in a good way: Creating desirable difficulties to enhance learning. In: Gernsbacher MA, Pew RW, Hough LM and Pomerantz JR (eds) *Psychology and the real world: Essays illustrating fundamental contributions to society*. New York: Worth Publishers, 2011, pp.56–64.
133. Nakamura J and Csikszentmihalyi M. Flow theory and research. In: Lopez SJ and Snyder CR (eds) *Oxford Handbook of Positive Psychology*. Oxford: Oxford University Press, 2009, pp.195–206.
134. Middleton AM and Ward TE. The pursuit of flow in the design of rehabilitation systems for ambient assisted living: A review of current knowledge. *Int J Amb Comput Intell* 2012; 4: 54–65.
135. Csikszentmihalyi M. *Beyond boredom and anxiety*. San Francisco: Jossey-Bass, 1975.
136. Charles D, Kerr A, McNeill M, et al. Player-centred game design: Player modelling and adaptive digital games. *Proceedings of the Digital Games Research Conference*. 2005, pp.00100.
137. Rebeiro KL and Polgar JM. Enabling occupational performance: Optimal experiences in therapy. *Can J Occup Ther* 1999; 66: 14–22.
138. Cameirão MS, Badia SB, Zimmerli L, et al. The rehabilitation gaming system: A virtual reality based system for the evaluation and rehabilitation of motor deficits. In: *Virtual Rehabilitation, 2007*. IEEE, 2007, pp.29–33.
139. Pirovano M, Mainetti R, Baud-Bovy G, et al. Self-adaptive games for rehabilitation at home. *2012 IEEE Conference on Computational Intelligence and Games (CIG)*. IEEE, 2012, pp.179–186.
140. Duff M, Chen Y, Attygalle S, et al. An adaptive mixed reality training system for stroke rehabilitation. *IEEE Trans Neural Syst Rehabil Eng* 2010; 18: 531–541.
141. Seo K, Kim J, Lee J, et al. Serious games for stroke patients: Attending to clinical staff's voices. *The 5th International Congress of International Association of Societies of Design Research*. 2013, pp.1–11.
142. Shin JH, Park SB and Jang SH. Effects of game-based virtual reality on health-related quality of life in chronic stroke patients: A randomized, controlled study. *Comput Biol Med* 2015; 63: 92–98.
143. Brown E and Cairns P. A grounded investigation of game immersion. *CHI'04 extended abstracts on Human Factors in Computing Systems*. ACM, 2004, pp.1297–1300.
144. Witmer BG and Singer MJ. Measuring presence in virtual environments: A presence questionnaire. *Presence* 1998; 7: 225–240.
145. Mihelj M, Novak D, Milavec M, et al. Virtual rehabilitation environment using principles of intrinsic motivation and game design. *Presence* 2012; 21: 1–15.
146. Wood RT, Griffiths MD, Chappell D, et al. The structural characteristics of video games: A psycho-structural analysis. *Cyberpsychol Behav* 2004; 7: 1–10.
147. Amory A, Naicker K, Vincent J, et al. The use of computer games as an educational tool: Identification of appropriate game types and game elements. *Br J Educ Technol* 1999; 30: 311–321.
148. Burke JW, McNeill M, Charles D, et al. Serious games for upper limb rehabilitation following stroke. *2009 VS-GAMES'09 Conference in Games and Virtual Worlds for Serious Applications*. IEEE, 2009, pp.103–110.
149. Ma M and Bechkoum K. Serious games for movement therapy after stroke. *2008 SMC 2008 IEEE International Conference on Systems, Man and Cybernetics*. IEEE, 2008, pp.1872–1877.
150. Burke J, Morrow P, McNeill M, et al. Vision based games for upper-limb stroke rehabilitation. *2008 IMVIP'08 International Machine Vision and Image Processing Conference*. IEEE, 2008, pp.159–164.
151. Goude D, Björk S and Rydmark M. Game design in virtual reality systems for stroke rehabilitation. *Stud Health Technol Inform* 2007; 125: 146–148.
152. Flores E, Tobon G, Cavallaro E, et al. Improving patient motivation in game development for motor deficit rehabilitation. *Proceedings of the 2008 International Conference on Advances in Computer Entertainment Technology*. ACM, 2008, pp.381–384.
153. Sucar LE, Luis R, Leder R, et al. Gesture therapy: a vision-based system for upper extremity stroke rehabilitation. *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, 2010, pp.3690–3693.
154. Lange B, Rizzo A, Chang C-Y, et al. Markerless full body tracking: Depth-sensing technology within virtual environments. *Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC)*. 2011.
155. Tsoupikova D, Stoykov NS, Kamper D, et al. Virtual Reality environment assisting post stroke hand rehabilitation: Case report. *Stud Health Technol Inform* 2013; 184: 458–464.
156. Shiri S, Feintuch U, Lorber-Haddad A, et al. A novel virtual reality system integrating online self-face viewing and mirror visual feedback for stroke rehabilitation: Rationale and feasibility. *Top Stroke Rehabil* 2012; 19: 277–286.
157. Merians A, Fluet G, Qiu Q, et al. Integrated arm and hand training using adaptive robotics and virtual reality simulations. *Proceedings of the 2010 International Conference on Disability, Virtual Reality and Associated Technology*. 2010, pp.213–222.

158. Friedman N, Chan V, Reinkensmeyer AN, et al. Retraining and assessing hand movement after stroke using the MusicGlove: Comparison with conventional hand therapy and isometric grip training. *J Neuroeng Rehabil* 2014; 11: 76.
159. Rego P, Moreira PM and Reis LP. Serious games for rehabilitation: A survey and a classification towards a taxonomy. *2010 5th Iberian Conference on Information Systems and Technologies (CISTI)*. IEEE, 2010, pp.1–6.
160. Alankus G, Lazar A, May M, et al. Towards customizable games for stroke rehabilitation. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2010, pp.2113–2122.
161. Charles D and McDonough S. A participatory design framework for the gamification of rehabilitation systems. In: Sharkey PM, Pareto L, Broeren J and Rydmark M (eds) *10th Intl Conf on Disability, Virtual Reality and Associated Technologies*. Gothenburg, Sweden, 2014, pp.293–296.
162. Burdea G, Cioi D, Martin J, et al. Motor retraining in virtual reality: A feasibility study for upper-extremity rehabilitation in individuals with chronic stroke. *Phys Ther* 2011; 25: 20–29.
163. Hung W and Van Eck R. Aligning problem solving and gameplay: A model for future research and design. In: Van Eck R (ed.) *Interdisciplinary models and tools for serious games: Emerging concepts and future directions*. Hershey, PA: IGI Global, 2010, pp.227–263.
164. De Kort YA and Ijsselsteijn WA. People, places, and play: Player experience in a socio-spatial context. *Comput Entertain* 2008; 6: 18.
165. Broeren J, Rydmark M, Björkdahl A, et al. Assessment and training in a 3-dimensional virtual environment with haptics: A report on 5 cases of motor rehabilitation in the chronic stage after stroke. *Neurorehabil Neural Repair* 2007; 21: 180–189.
166. Kwakkel G. Impact of intensity of practice after stroke: Issues for consideration. *Disab Rehabil* 2006; 28: 823–830.