The Design of a Virtual Reality Game for Stroke-Induced Attention Deficits

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Abstract
Hemispatial neglect is a spatial attention deficit that occurs in 25 up to 50% of stroke survivors and has a negative impact on functional recovery. Despite an increased understanding of the mechanisms underlying hemispatial neglect, there is no effective treatment yet. In particular, the transfer of treatment effects to daily life is often missing. A more ecological approach to rehabilitation may therefore produce better treatment effects. Here we present the design of a virtual reality game for stroke patients with spatial attention deficits. Moreover, we present the use of our 'Intervention Logic – Game Mechanic' model which details how theory-grounded intervention principles were translated into game mechanics and desired treatment outcomes. Additionally, we demonstrate how simulations on the basis of player models aid in designing a dynamic difficulty adjustment algorithm and reduce the need for elaborate gameplay testing.

Author Keywords
Virtual reality; stroke; hemispatial neglect; attention; rehabilitation; dynamic difficulty adjustment.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous;

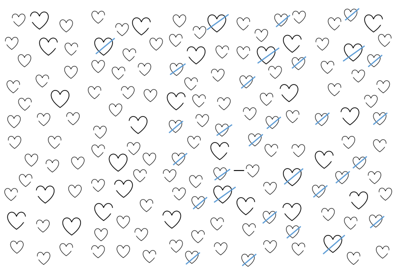

Figure 1. The hearts cancellation task of the Oxford Cognitive Screen. The closed heart shapes located on the right side of the page are cancelled, while the closed heart shapes on the left side are not.

Introduction

Hemispatial Neglect

Hemispatial neglect is a condition in which stroke survivors with unilateral (one sided) brain damage fail to attend the contralesional (opposite) side of space [16]. This condition restricts daily life functioning and limits recovery of other functions affected by stroke, such as the use of the contralesional limb [7]. Neglect is often diagnosed by measuring the patient's visuospatial search pattern with a target cancellation task, for instance a task in which patients must cross out closed heart shapes, while ignoring broken heart shapes. Neglect patients fail to indicate the targets on the contralesional side of the page (Figure 1, [9]). This spatial attention bias can also affect sensory domains other than vision, such as audition or somatosensory processing [9]. In addition, it has been shown that the spatial attention bias in neglect patients is accompanied by non-spatial deficits such as poor sustained attention [18].

Rehabilitation of Neglect

Many endeavors have been made to rehabilitate hemispatial neglect, but most approaches failed to generate long-lasting treatment effects that transfer into daily life [5,13,19,21,22]. Additionally, due to a lack of disease insight, it can be difficult to motivate neglect patients to engage in their treatment. A virtual reality (VR) game could tackle both obstacles of transfer and engagement, by training patients in a realistic environment in 3D space and by motivating engagement through sensory immersion and gaming mechanics [1,2,6,15,20,23,27,29]. VR may especially increase transfer of learning by enabling learning situated in an environment resembling real life [8]. Furthermore, engagement with learning in VR may be better due to a high sensory presence [8].

Lately, dynamic difficulty adjustment (DDA) has been recognized as an important feature of games, balancing game challenge against player skill for an optimal experience [3,10,17]. Despite the fact that DDA algorithms can tailor interventions to the skill level of the individual patient and can make training more efficient by targeting the intervention more on the skills that must be trained, it has not been thoroughly investigated whether DDA algorithms can produce stronger rehabilitation effects in stroke patients. Given the large inter-patient variability in post-stroke cognitive status [9], DDA algorithms may be particularly useful for this population.

In this paper, we present the design of an adaptive VR game for patients who have had a right-hemispheric stroke with spatial attention deficits, using the Oculus Rift CV1 and the Oculus touch controllers, developed in the Unity 3D Engine. In particular, we present two contributions to the CHI PLAY community. First, we present the use of our 'Intervention Logic – Game Mechanic' model which details how our theoretical principles were translated into game mechanics and desired treatment outcomes. The use of our 'Intervention Logic – Game Mechanic' model can act as an inspiring example for other developers of serious games. Second, we demonstrate how simulations based on a patient model can aid the development and optimization of a DDA algorithm. The result is a VR game grounded in theory and tailored to the patient's skill level.

Translating Interventions into Game Mechanics

During the design and development of this game, a team of engineers, designers and psychologists communicated with one another to align the game mechanics, the game art and storyline with the intervention logic and treatment goals. Therefore, we used a game playbook as a means for effective communication [12]. A game playbook is a combination of a game design document which is typically used in the field of game design, *and* a logic model and intervention manual, which is typically used in health research [12]. The game design document contains information about the aesthetics and narrative of the game, the player's objectives, the progression model, the way in which feedback is provided to the player and a description of the user interface. The intervention manual and logic model describe the principles of the intervention, the ultimate goal of the intervention and how both will be operationalized.

Central to the game playbook is the model that maps intervention components to game mechanics and desired (behavioral) outcomes. The authors who proposed the game playbook used this method for the development of a game to prevent HIV infection in adolescents [12]. In our project, we tailored the game playbook to the development of a cognitive training (Figure 2). In the following paragraphs, we present the design of our game alongside the different elements of our 'Intervention Logic – Game Mechanic' model.

The Intervention Components

At the moment, the dominant theory to explain neglect symptoms states that patients have an asymmetrical priority map [25]. The priority map is a topographic representation of our environment in which each location is associated with a priority value, which is computed by combining the saliency of a stimulus and the task- or behavioral relevance of the stimulus [4]. The higher the priority in the map, the more likely it is that the corresponding location will be attended. Thus, the priority map guides our information selection in space. Patients with neglect have a spatially biased priority map, in which contralesional locations have low priority values and therefore their visuospatial exploration is not oriented towards contralesional space [25]. Additionally spatial attention deficits in neglect patients are worsened by a reduced ability to sustain attention on a task for extended time periods [18].

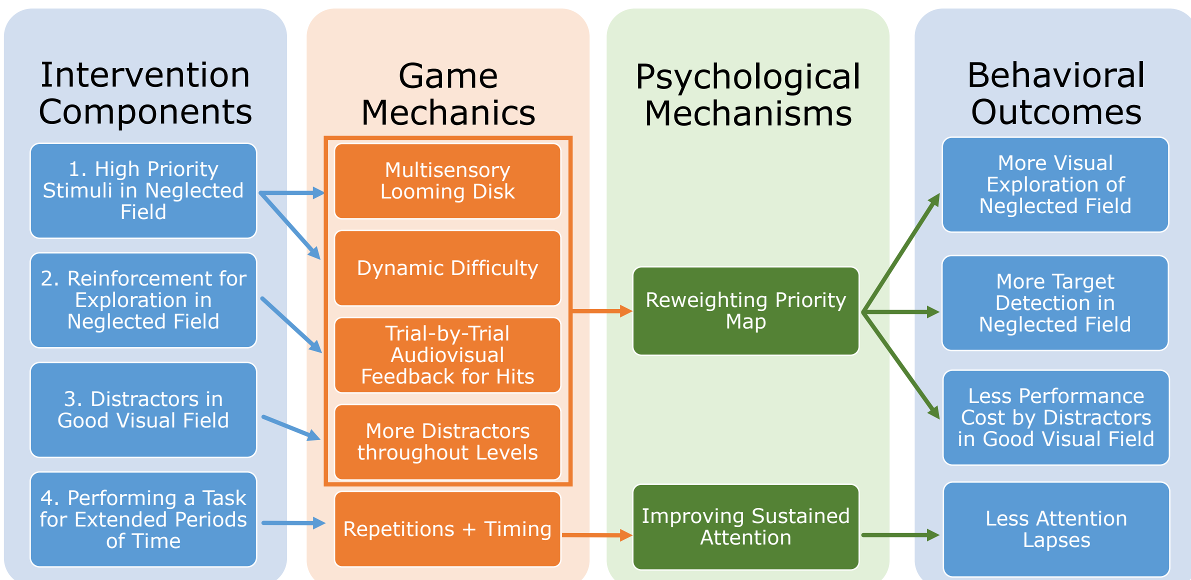

Figure 2. The intervention logic – game mechanic model clearly shows how intervention components translate into game mechanics and desired outcomes. The psychological mechanisms are depicted in green to represent latent constructs.

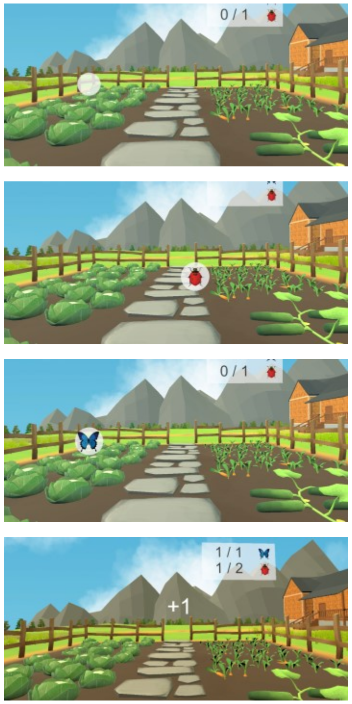

Figure 3. The first image illustrates the disk. After the presentation of this disk, a blue butterfly or red ladybug is presented (image 2, 3). After a correct response, feedback is provided (image 4).

We hypothesize that hemispatial neglect can be treated by four intervention components (Figure 2): 1) the presentation of high priority stimuli on the neglected side, 2) the positive reinforcement of visuospatial exploration of the neglected side, 3) the presentation of task-irrelevant stimuli (distractors) on the ipsilesional (same side as brain lesion) side and 4) incentives to perform the task for an extended time period. The first three components aim to reweigh the priority map and consequently increase visuospatial exploration in the neglected field after training. The last component aims to improve sustained attention in daily life, which should result in less attention lapses when performing a repetitive task after training.

From Intervention Components to Game Mechanics

Multisensory looming disk

It was chosen to operationalize the “high priority” stimulus (the first intervention component) as a multisensory expanding (looming) stimulus, because previous studies have shown that looming and multisensory stimuli have more chance to enter awareness compared to contracting and unisensory stimuli in neglect patients [11,14]. During the game a disk is presented to the player. This disk expands and contracts in size according to a rhythm (looming). The presentation of the disk coincides with the presentation of a sound that matches in frequency (multisensory looming). This multisensory looming disk predicts the location where the next target will be presented. After a couple of seconds, the player must discriminate between two types of target stimuli (e.g. a blue versus a red butterfly) that are presented at the center of the disk (Figure 3). To discriminate between the two targets, the player receives a limited time window. If the player has not given a response within this time window or if he has given an incorrect response within this time window, the response is considered a miss. The player must perform multiple trials (a sequence of presentation of a disk, a target and a response time window) of this task in our game. To motivate patients to perform this repetitive task, the targets that must be discriminated and the environment changes after each two levels of the game.

Dynamic Difficulty Adjustment (DDA)

We developed a DDA algorithm to adjust the location of the disk and target stimuli in real-time as a function of the player’s performance. The primary goal is to present high priority stimuli more frequently in the neglected field than in the good field. Since the extent of the neglected field may vary among patients, a DDA algorithm could perform better at this goal than a fixed difficulty design. A second goal of this algorithm is to adjust the difficulty of the game to an appropriate level for each player. The adaptive algorithm is detailed further down below.

Trial-by-Trial audiovisual feedback

The second intervention component is translated into a feedback mechanism that mainly uses positive reinforcement. Players always receive a point accompanied by a rewarding sound when correctly classifying the target stimulus. When players do not respond or incorrectly classify a target stimulus, a warning sound is presented, but their score is not affected.

Distractors

As for the third intervention component, higher levels are characterized by the presence of more salient task-irrelevant stimuli (distractors) in the environment. This procedure aims to train the patients’ ability to attend to

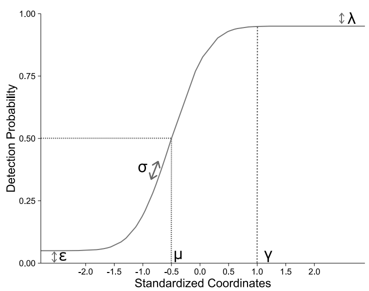

Figure 4. Model of left sided neglect.

the neglected field, even when there are interesting stimuli present in their good visual field.

REPETITION AND TIMING

Finally, for the fourth intervention component, in between each trial in which patients must discriminate between two target stimuli there is a pause. This pause makes the target discrimination task more slow-paced than traditional games and taxes sustained attention. During this repetitive and slow-paced task, the players are externally cued to maintain their focus on the task at hand. If they miss a target (due to an attention lapse) a sound is presented to alert them about the missed target. This game mechanic is based on the self-alerting training strategy [24,26]. By externally alerting the player, attention lapses during gameplay will occur less often. Through this procedure, patients may learn to internalize these alerting events and consequently maintain better cognitive control on tasks in daily life after training.

Simulations to Optimize Algorithms

As aforementioned, DDA is desirable to ensure that a game matches player skills [17]. In current game development, these algorithms are often optimized through multiple rounds of user testing with the target group [3,28]. However, repeated data collection within a sufficiently large population of stroke survivors (with hemispatial neglect) is difficult. To overcome this challenge, we used simulations based on a model of our players. The aim of the simulations was to reveal how the difficulty of the game adapts to the characteristics of the player. The goals of the algorithm are to: 1) present stimuli in the neglected field and 2) adjust the difficulty of the game at an appropriate level for each player.

The Adaptive Algorithm

A truncated Gaussian distribution determines the location of targets in the game. The mean of this distribution represents the location where targets will most likely appear. The mean is initialized at the center of the visual field (assuming the observer looks straight ahead) and is adjusted based on the median locations of missed targets at a fixed rate.

The Player Model

Instead of using empirical data acquired through user evaluations with neglect patients, we simulated data. Our model (Equation 1) has to represent the visuospatial asymmetry that characterizes neglect patients [7,16]. In our model, the probability of a correct response ($G(x, d, n)$) depends on the stimulus location (x), according to a cumulative Gaussian distribution with μ (the mean) and σ (the slope). The cumulative Gaussian is restricted to one side of space by a boundary (γ) between the neglected and the good visual field. The probability of a correct response also depends on a failure percentage independent of the target location (λ) and a guess percentage (ε) (Figure 4). Learning was modeled by shifting the initial value of γ (γ_0) to the left side as a function of the already

$$G(x, d, n) =$$

$$\begin{cases} \psi(x, d \mid \mu, \sigma, \lambda, \varepsilon, \alpha) = \varepsilon + [1 - \varepsilon - \lambda - \alpha . d] . F(x; \mu, \sigma); & x \leq \gamma_n \\ \psi(x \mid \lambda) = 1 - \lambda; \;\; \lambda \epsilon [0, 1]; & x > \gamma_n \\ \gamma(n \mid \theta) = \gamma_0 - (\theta . n) \end{cases}$$

$$with\ d, \varepsilon, \alpha, \lambda, \theta \ \epsilon \ [0, 1] \ and \ \sigma > 0$$

Equation 1. Mathematical formulation of the model.

completed number of trials (n) and the learning rate of the player (θ). A smaller γ represents a smaller neglected field. Distractors (d) reduce the probability to detect targets located in the neglected field according to a fraction representing distractor sensitivity (α).

Simulations
The probability of a correct response for each trial can be predicted based on this model. This probability is transformed into a hit or miss according to a Bernoulli distribution and the resulting pairs of coordinates, and hits or misses of each trial are used as input for the DDA. The mean of the truncated Gaussian distribution that determines future target locations is shifted to the location where previous targets were missed. Then, the probability of a correct response for these new locations can be estimated and new trials can be simulated. This procedure can be repeated for different combinations of player and game features to reveal how the game adapts to different types of players. For instance, based on this method, we can compare the hit rate and progress throughout the game of a player that learns to a player that does not learn. Additionally, we can study the effect of the frequency of updating the game on the hit rate of players and their progress throughout levels. These comparisons can reveal whether the DDA results in a game that matches the players' skill and can inform the developer about the best parameter choices for the game, especially when this player model is empirically validated.

Discussion and Future Work

We presented the design of a new adaptive VR game for the treatment of attention deficits after stroke. We demonstrated the use of our Intervention Logic – Game Mechanic model to ensure that the goals of the intervention match the game design. We also presented how simulations based on a player model can help pre-test DDA algorithms. In the future we plan to test whether neglect patients truly benefit from this adaptive VR game and explore how the game context is experienced by older adults. We expect that rehabilitation effects are strengthened by individualizing treatment through adaptive procedures, by motivating treatment engagement through VR and gaming elements and by training stroke patients in a realistic 3D environment.

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