MemSpark: Artificially Intelligent Virtual Reality System for Non-Intrusive Therapy and Evaluation of Dementia

Background

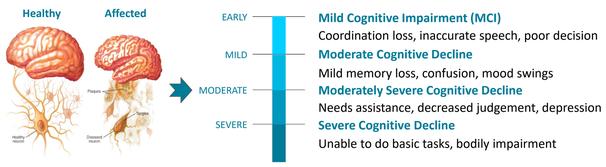


Figure 1. Impact of neurodegeneration

Mayo Clinic. (2021, June 26). Alzheimer's disease - symptoms and causes. Mayo Clinic; Mayo Foundation for Medical Education and Research (MFMER). https://www.mayoclinic.org/diseases-conditions/alzheimers-disease/symptoms-causes/syc-20350447

Dementia is a neurodegenerative disease caused by an abnormal accumulation of proteins in the brain. This results in ruptured connections among neurons which in turn causes significant brain changes. These changes manifest through psychological and physical symptoms, impacting daily life of a person with dementia (PwD).

Current Therapy Options

While there is no cure for dementia, current mainstream pharmacological and therapeutic options also fail to reduce the progression. They falsify the improvements, or cause significant physical and mental side effects, leading to poor quality of life (QoL) and shorter lifespan. Addressing such shortcomings need a better solution.

Symptomatic	Invasive	Ineffective
Address the symptoms but not the root cause.	Enters body, causes significant side effects.	Does not significantly slow the progression.
• Music therapy • Behavioral therapy • Animal therapy	• Donepezil • Rivastigmine • Memantine	• Occupational therapy • Reminiscence therapy • Art therapy

Figure 2. Limitations of current mainstream therapeutic options

Engineering Solution

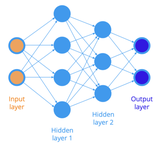
Virtual Reality

VHIL. (n.d.). VHIL. Retrieved April 27, 2023, from https://stanfordvr.com/

Virtual reality (VR) mimics brain's ability to create a mental map of an environment using senses. Utilizing VR for a therapeutic intervention has proven to enhance neural connections leading to heightened neuroplasticity and cognition among children and seniors.

To address the shortcomings of current therapies an immersive set of serious games could be developed using VR. Engaging a PwD through a gaming experience helps avoid intrusion and the side effects of a typical task-based therapy such as anxiety, frustration, self-pity and feeling of getting lost.

Artificial Intelligence



Cristina, S. (2021, August 22). Calculus in Action: Neural Networks. Machine Learning Mastery. https://machinelearningmastery.com/calculus-in-action-neural-networks/

A biologically inspired artificial computational network such as multilayer perceptron (MLP) could help automate the profiling/evaluation procedure. In current profiling process, a dementia expert collects cognition data through various tasks and analyzes over days to determine PwD's dementia level and progression. Using an MLP with backpropagation learning algorithms, can reduce time for such supervised procedure to seconds after training. An MLP's flexibility to customize structure, algorithm, data preprocessing, and measure effectiveness through overfitting, and sensitivity analysis make it most suitable for this problem.

Goals

Therapy

1. Requires no more than 30 minutes per session.
2. Therapy is non-intrusive and increases focus.
3. Produces statistically significant improvement in cognitive function and quality of life.
4. Does not involve dementia expert.
5. Can be validated with 10 patients over 3 months.

Profiling

1. Profiles a patient's cognitive abilities with 90% accuracy.
2. Produces cognition profile within 1 minute.
3. Does not involve profiling specialist.
4. Trains on at least 1700 data points: 1250 training, 250 testing, 200 validation.

System Design

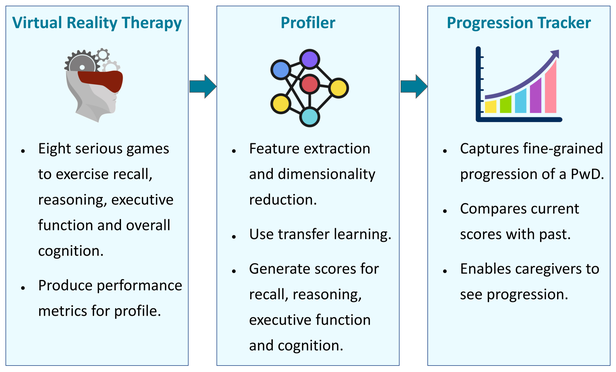


Figure 3. MemSpark system design

To accomplish the research goals, a system was developed in three parts: a VR therapy, profiler, and progression tracker. The VR therapy consists of eight serious games that exercise various parts of the brain that get affected by dementia. Once performance metrics were extracted from the game, they were inputted into an MLP neural network that produced a complete cognition profile. This cognition profile was displayed on an intuitive dashboard along with previous data for a PwD.

Variables

Independent	Controlled	Dependent
1. Accuracy of response 2. Speed of response	1. Recall Score 2. Reasoning Score 3. Executive function Score 4. Overall cognition Score	1. Distraction 2. Intrusion 3. Physical movement

Experimentation

1. Therapy Design

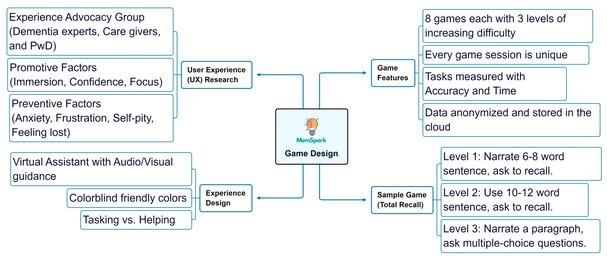


Figure 4. Methodology to design virtual reality based therapy

2. Therapy Coverage

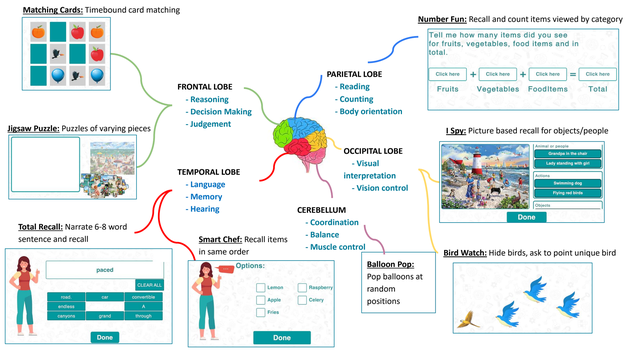


Figure 5. Virtual reality games that exercise every part of the brain

3. Data Organization

Collection	• 14 patients: 10 experimental and 4 control • Duration 6 months: Experimental group weekly, Control group monthly • Data diversity: Varying gender, age, and severity
Formatting	• 8 games with 3 levels of increasing difficulty • Random task selection from each level from a set of 10 • Level completion measured using Accuracy and Time
Pre-Processing	**Weighted average statistical analysis** was done to reduce the dimensionality of the data from 48 to 8 features. Normalized data from VR game to be a decimal value between 0 and 1.

Figure 6. Data organization approach

4. Feature Extraction

Behavioral Features	Mathematical Features
1. Recall: Remember information over short/long periods of time **2. Reasoning:** Make logical inferences from information **3. Executive Function:** Efficient decision making	**1. Accuracy:** How well a task was completed **2. Time:** How long it took to complete the task

Figure 7. Features derived to develop artificial neural network

5. Homogeneous Transfer Learning

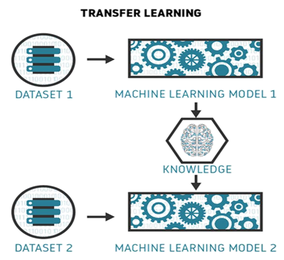


Figure 8. How transfer learning works

Machine Learning Smart Inventory Tracking with Raspberry Pi. (n.d.). Hackster.io. https://www.hackster.io/supperted825/machine-learning-smart-inventory-tracking-with-raspberry-pi-d866c7

To build an ideal AI model for profiling, a diverse and large labeled training dataset with same distribution as the test data was desired. However, creating such training data would require over 100 patients, and 12 months time, which was unrealistic.

This challenge was overcome by applying homogeneous multi-model transfer learning on an **existing dataset of 200 patients** that consisted of the same input and corresponding output scores. A **pre-trained neural network** which used data from 14 VR therapy participants**,** was **re-trained** on 200 patients' data. This increased 1,792 data points to 3,392 upon which a 70-20-10 training-testing-validation split was applied.

6. Neural Network Optimizations

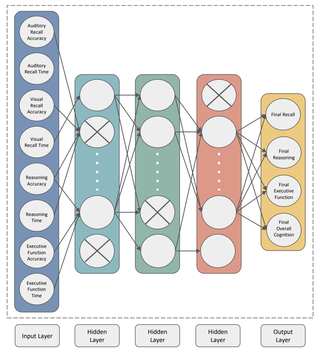


Figure 9. Fully-optimized multi-layer perceptron neural network

Structural

Optimizing architecture.

- **Large-to-small approach:** Large AI model was trained on data and superfluous synapses, neurons, and layers were removed.
- **Neural network layers:** an input layer (8 neurons), 3 hidden layers (120, 170, and 50 neurons), and an output layer (4 neurons).

Parametric and Functional

Optimizing parameters, activation, and backpropagation.

- **Activation:** Gaussian Error Linear Unit (GELU).
- **Backpropagation algorithm:** RMSProp Optimizer.
- **Hyperparameter tuning:** epochs, learning rate, batch size, and dropout rate.

7. System Implementation using Cloud Computing

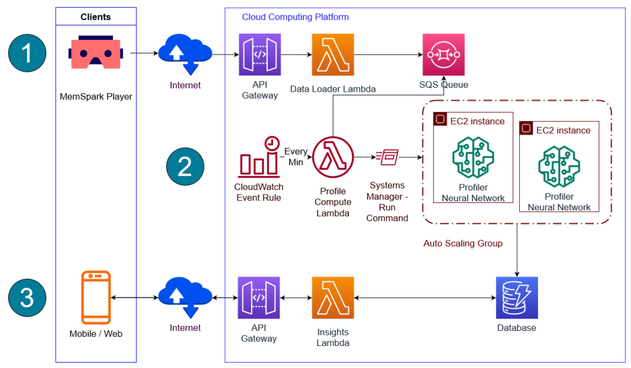


Figure 10. MemSpark system to combine therapy, profiler and progression tracker using cloud-computing platform

Results

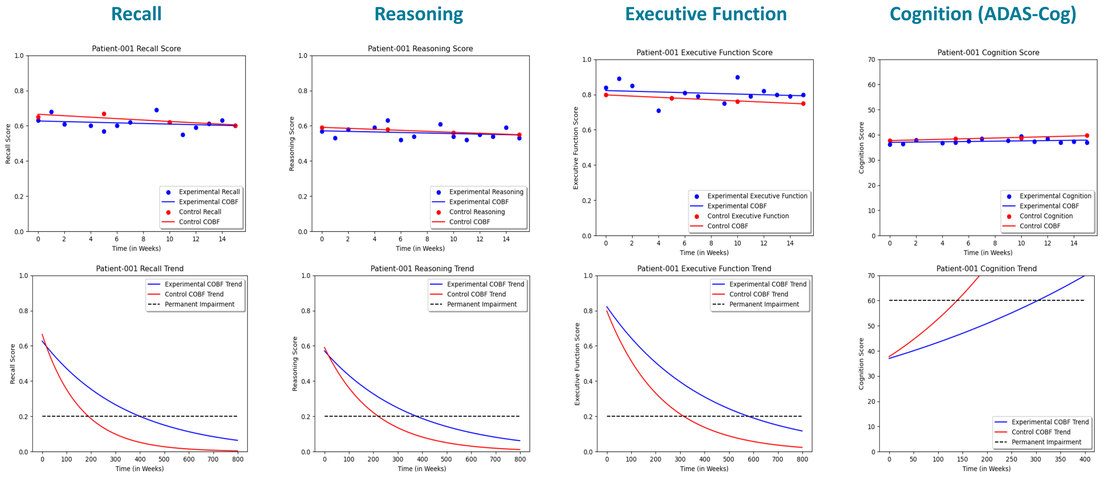


Figure 11. Therapy performance for a PwD in control group against experimental AND Prediction of progression for control and experimental group using curve of best fit for 800 weeks

Graphs above provide insight into performance of one PwD. Graphs in the top row indicate the PwD's performance (in Blue) against the control group (in Red). Across all features, the decline, indicated by the slope, is significantly lower in the EG than the CG. The graphs in the bottom show the projections for progression over the span of 8 years. The dotted line indicates a threshold for cognitive impairment beyond which a PwD is unable to function. The PwDs in EG would reach this threshold ~180 weeks after the CG PwDs, elongating their lifespan by over 3 years.

*** All tables, graphs, and figures were created by the Finalist unless otherwise cited.**

Evaluation

Therapy Metrics Evaluation

1. Change in Key Performance Indicators

Δ Metrics	Range	EG	CG
Recall	0 to 1	-0.01	-0.05
Reasoning	0 to 1	-0.03	-0.06
Executive Function	0 to 1	-0.02	-0.03
Cognition	0 to 70	+1.94	+5.50
Quality of Life	16 to 112	-2.53	-6.05
Working Memory Index	0 to 145	-4.24	-10.38

Figure 12. Delta metrics to quantify VR therapy performance

2. Statistical Significance

The decay rate, quality of life, recall, and WMI, of all PwD in the experimental group is statistically significant at the p = 0.01 level. For recall, reasoning, and overall cognition, the decay rate is statistically significant for all patients at the p = 0.05 level.

3. Decay Constant & Prolonged Life Expectancy (PLE)

The decay constant is equivalent to the value k in the following differential equation:

$$\frac{dC}{dt} = -kt.$$

The average decay constant for the experimental group was **0.0016** and **0.0034** for the control group. The average PLE was approximately equivalent to the life expectancy for the corresponding control patient. On average, MemSpark's VR Therapy was able to double the remaining lifespan of a PwD.

4. Performance Relative to Other Therapies

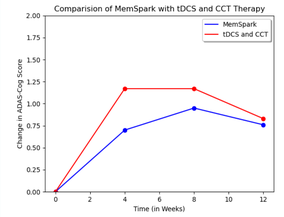


Figure 13. Comparing effectiveness of MemSpark and other mainstream therapies such as tDCS and CCT

Profiler Metrics Evaluation

Neural Network Performance

Metric	Value
Mean Absolute Percentage Error (MAPE)	0.038
Accuracy = 100 x (1 - MAPE)	96.18%
Mean Absolute Error	1.031
Root Mean Squared Error	2.935
Total of data points (Training + Testing + Validation)	3,392 (2400 + 600 + 392)
Profiling Time (In Seconds)	1.96

Figure 14. Metrics to quantify profiling neural network's effectiveness

Conclusion and Impact

Effective

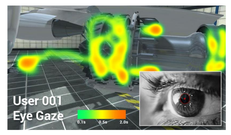
1. Produces quantifiable results: 65% slower decline, 59% better QoL, 60% better working memory
2. Produces profiles in 2 seconds with 96.18% accuracy.
3. Targets all parts of brain in nonintrusive manner.
4. Can double the remaining lifespan of a PwD.
5. PwDs enjoy therapy, removing anxiety and frustration posed by current therapies.
6. Ideal solution for early detection, diagnostics and prevention of dementia.

Accessible

1. Doctors can replace interview-based profiling with MemSpark.
2. Senior care centers can replace group therapies with MemSpark's personalized care.
3. Accessible to around 40% of dementia population (third-world countries), lacking access to a doctor (the largest contributor to dementia's growth).
4. Reduces long-term care for a PwD from $69,000/Yr. to $20,000/Yr.
5. Has potential to save millions of lives through cloud-based automated solution.

Future Work

- Create an adaptive game experience.
- Select tasks within the level with weighted probability (additional dimension of difficulty).
- Do eye-tracking to directly measure features such as coordination.
- Add games for improving physical functions.
- Use on-the-edge computing to reduce the cost of computing in cloud.



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