BrainIn: A Data-driven Software System for Neurorehabilitation of People with Acquired Brain Injuries

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Abstract: The current model of neurorehabilitation provides comprehensive care (neurologist, physiotherapist, occupational therapist, psychologist, speech therapist) in the acute phase of acquired brain injuries during hospitalization in some countries. However, follow-up care is insufficient or completely absent, especially for disadvantaged people. Increasing the availability, effectiveness and efficiency of neurorehabilitation care is beneficial both socially and economically. The BrainIn project aims to improve the quality, effectiveness, and efficiency of neurorehabilitation procedures in both the acute phase and long-term home rehabilitation phase. Moreover, its goal is to facilitate and accelerate the return of the affected people to their families, social, and working life. The BrainIn project is freely available as a web application (https://brainin.kiv.zcu.cz/). It is adapted to the needs of therapists and patients who have experienced acquired brain injuries.

1 INTRODUCTION

This paper deals with the neurorehabilitation of people suffering from acquired brain injuries (ABIs) and opportunities to improve its availability, effectiveness and efficiency. First, it presents an overview of studies, approaches, questions and results achieved in the ABI neurorehabilitation and then introduces an online data-driven software system BrainIn that provides ABI people, their families and therapists with various neurorehabilitation tasks. Moreover, the BrainIn system enables the personalization of neurorehabilitation tasks, facilitates remote cooperation among ABI people, their families and therapists and collects behavioural data that can help to improve neurorehabilitation procedures.

The term acquired brain injury (ABI) refers to any brain injury that occurs after birth, i.e. is not hereditary, congenital, degenerative, or induced by birth trauma. Medical disciplines use various classifications for ABIs, including traumatic brain injury (TBI) and non-traumatic injuries such as infection, disease, stroke, brain tumour, lack of oxygen, a blow to the head, poisoning, and alcohol/drug abuse. ABI results in a change to the brain's neuronal activity, which can lead to changes in the physical and sensory abilities, behaviour and personality, metabolic activity, attention, memory, communication abilities, thinking and learning or can cause other medical troubles such as epilepsy.

It is generally difficult to predict the long-term effects and consequences of ABI. These are different for each individual and range from mild to severe. People usually suffer from increased mental and physical fatigue and decreased general abilities to plan and solve problems and process information. These changes require a period of adjustment, both physically and emotionally, and affect the individuals suffering from ABI and their families, friends, and caregivers.

There is general agreement that the neurorehabilitation care of people with ABI is very demanding. It involves an overall systematic and interdependent cooperation of experts such as neurologists, physiotherapists, occupational therapists, psychologists, speech therapists, and above all, ABI people themselves and their family members. The big questions (to which we have only very limited answers) are how to target and organize neurorehabilitation care to make it effec-

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tive and efficient for all involved individuals in their daily routines, how to provide reasonable (sufficient and non-annoying) feedback among all involved people and implement innovative procedures improving a long-term therapy.

The paper itself is organized as follows. The State of the Art section provides a short overview of available resources: mainly review papers and computer-based neurorehabilitation papers are provided. The third section introduces the core concepts of the BrainIn software system. Then the fourth section describes the system implementation. The fifth section gives an overview of groups of neurorehabilitation tasks available in the BrainIn system. The sixth section provides a study on using the system by a long-term ABI patient. The last section comes with concluding remarks.

2 STATE OF THE ART

Although we might assume that the questions of effectiveness and efficiency of the neurorehabilitation interventions should have already been resolved, this is not the case. This section provides a state-of-the-art overview of ABI rehabilitation, focusing mainly on its effectiveness and efficiency. Since hundreds of studies were carried out and published to aim at different ABI rehabilitation approaches, usually review papers with their results and conclusions are presented.

The efficacy of acquired brain injury rehabilitation is investigated in the systematic review given in (Cullen et al., 2007) to provide guidance for clinical practice. The authors conclude that most interventions have only been supported by limited evidence, although positive outcomes are documented. These include, e.g. moderate evidence that inpatient rehabilitation results in a successful return to work or that direct patient involvement in neurorehabilitation goals results in significant improvements in reaching and maintaining those goals. The authors conclude that there is a need for studies of improved methodological quality into ABI rehabilitation.

(Turner-Stokes and Wade, 2015) present a systematic review of 19 studies involving 3480 people of working age. They claim that systematic reviews demonstrate that multi-disciplinary rehabilitation is effective in the stroke population, in which older adults predominate. However, the evidence for the effectiveness of rehabilitation following ABI in younger adults has not been established. They conclude that different interventions and combinations of interventions are required to meet the needs of patients with different problems.

Efficacy of neurofeedback interventions for cognitive rehabilitation following brain injury is systematically reviewed in (Ali et al., 2020) concluding that 'given the limited quantity and quality of the available research, there appears to be insufficient evidence to comment on the efficacy of neurofeedback therapies within an ABI rehabilitation context' and providing recommendations for future research.

A scoping review (Stolwyk et al., 2021) examines the literature related to economic evaluations of neuropsychological rehabilitation in individuals with ABI. There were included studies published between 1995 and 2019 with a study population of adults aged 18 years or more with any ABI aetiology. The authors state (among other conclusions) that most studies have documented cost savings from providing various models of multi-disciplinary inpatient or outpatient rehabilitation. On the other hand, these benefits were estimated without a control group. Only a few eligible studies included a cost-effectiveness analysis that yielded mixed evidence for interventions considered cost-effective for ABI.

A systematic review of the use of computerized cognitive rehabilitation of attention and executive function in ABI provided in (Bogdanova et al., 2016) concludes that preliminary evidence suggests improvements in cognitive functions following computerized rehabilitation for ABI populations. However, it is also stated that further studies are needed to address issues such as small sample sizes or inadequate control groups.

A systematic review of outcomes of computerized cognitive training (CCT) in adults with ABI using the International Classification of Functioning, Disability and Health (ICF) is given in (Sigmundsdottir et al., 2016). One of the conclusions is that there is much research examining the efficacy of CCT, but relatively few Level 1 (randomized controlled trials with a PEDro-P score $\geq$ 6/10) studies and evidence is limited mainly to body function outcomes.

Computer-based cognitive interventions in ABI are systematically reviewed in (Fernández López and Antolí, 2020). The authors conclude that such interventions might be beneficial for ABI people to improve their visual and verbal working memory, although no effect was found in other cognitive domains.

The efficacy of ICT-Based neurocognitive rehabilitation programs for ABI was systematically reviewed in (Geraldo et al., 2018). Most of the thirty-one studies use a pre-post methodological design, with few performing assessment moments during intervention or follow-up. Attention, memory, and executive functions were the variables mainly considered by these studies to assess neurocognitive rehabilitation programs efficacy. The studies present a considerable heterogeneity of the instruments and methods used, even for the same assessment purpose; a lack of consensus regarding assessment protocol is well visible.

A systematic review in (Resch et al., 2018) examines studies investigating cognitive rehabilitation interventions for children with ABI, also focusing on identifying effective (computerized) drill-based exercises. Authors conclude (preliminarily, due to small sizes and heterogeneity of included studies) that available evidence suggests that multi-component rehabilitation, including drill-based training, is most promising and can lead to improvements in children's cognitive and psychosocial functioning ABI.

A clinical review dealing with neurorehabilitation of traumatic brain injuries (TBIs) is presented in (Oberholzer and Müri, 2019). The authors point out specific characteristics of TBI individuals compared to individuals with ABIs. They address questions on timing and existing evidence for various rehabilitation programmes and their impact on the outcomes in TBI rehabilitation. They also state that there are currently no international guidelines regarding treatment in the early rehabilitation phase for patients with severe TBI and that only a few studies have investigated the effect of integrating rehabilitation into acute TBI care.

A literature review of immersive virtual reality in TBI rehabilitation is provided in (Aida et al., 2018) concluding that "while the current literature generally offers support for the use of VR in TBI recovery, there is a paucity of strong evidence to support its widespread use".

A qualitative study aimed to explore the needs of individuals with TBIs and their loved ones (Lefebvre and Levert, 2012) point out that health care professionals should adopt a personalized approach to respond to needs related to the evolution of information, support, and relationships among them, individuals with TBIs and their loved ones.

A systematic review (Coxe et al., 2020) dealing with telebehavioral interventions for family caregivers of individuals with TBI concludes that caregivers generally express positive outcomes related to telebehavioral interventions, but low diversity of samples prevents generalizing these outcomes.

A critical review of the literature (Fetta et al., 2017) dealing with the efficacy of computer-based cognitive rehabilitation interventions on cognitive performance after mild TBI and ABI concludes that computer-based interventions seem promising when improving working memory in individuals with ABI. However, there is no evidence that currently available interventions are specific to mild TBI.

To summarize the state-of-the-art section, we can argue that many studies describe ABI/TBI rehabilitation's success. On the other hand, only a small part of the studies was carried out so that the success of the rehabilitation, or rather the rehabilitation procedures used, was proven. This can also be stated in the case of computer-based rehabilitation. All in all, the evidence that targeted rehabilitation procedures lead to significantly better results than any rehabilitation, even if based on everyday human activities, is not convincing.

Finally, we can modestly state that various stimuli that motivate ABI people to be active and improve their abilities and skills have a rehabilitative character. Then, a computer-based system providing tasks targeted to improve various skills and abilities can help ABI people, their families, and therapists in the long term.

3 BrainIn SYSTEM

BrainIn is an online software system (web application) for the neurorehabilitation of patients with ABI. It is designed for patients in institutional and home care, their families, and therapists and enables the computerized definition, execution, and basic evaluation of personalized neurorehabilitation tasks of varying degrees of difficulty for each patient. The therapist defines the sets of personalized neurorehabilitation tasks, and the patient then performs them with the help of the therapist, the family, or completely alone. The main advantage of the BrainIn system is the possibility of personalization of the tasks by the therapist, the creation of exercises of different difficulty levels, the organization of activities in packages, and the readiness of the system for partially automated evaluation of the patient's results and the subsequent use of machine learning methods to make recommendations for personalized therapies.

The BrainIn system is based on task templates with input variables for adjusting each task for an individual patient. These input variables must be set before execution. Their setting occurs in the task that runs the program. These tasks are easily editable, and it is easy to create a similar version (for example, with a different number of rounds, other pictures, questions, etc.). The exercise for each patient typically forms a package consisting of multiple tasks.

We have introduced the terms template, task, and package.

- A template is both the program itself and a web form defining input and output variables. Input

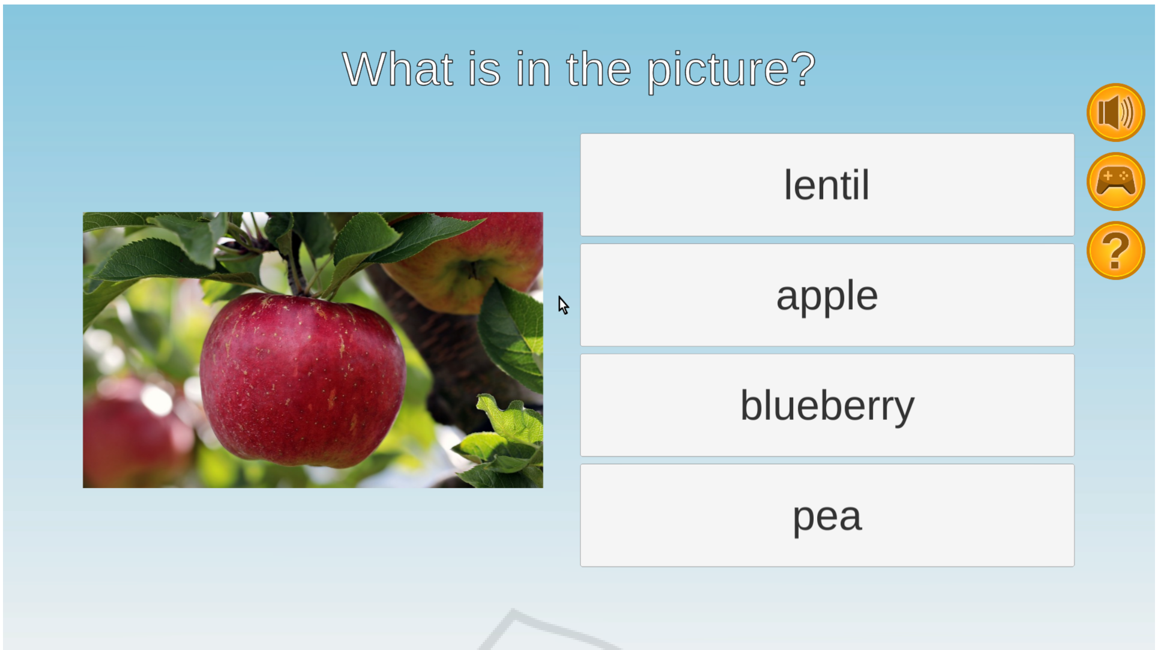

Figure 1: Vocabulary task. The patient is asked to select the caption corresponding to the picture shown with a mouse click. It is possible to use help (e.g., '50:50' to hide two wrong options) by clicking on the question mark button.

variables define parameters of the task typically used for modifying the difficulty level and personalization. For example, the therapist can select familiar images for each patient (e.g., towns in their neighbourhood), the number of hints, or highlight some letters related to the task. The output parameters describe the performance and recordings of each task execution. For example, the success rate of the answers, the number of hints used, or event recordings, such as a history of mouse clicks. Examples of input and output parameters are in Table 1. The code is shared for all tasks created by the same template.

- A task is a web form that sets the input variables defined in the template, the setting of which is necessary to run the template program.
- The package is a set of tasks. Our concept is a web form that creates a list of tasks.

The BrainIn users can be assigned a total of five roles that modify their capabilities and behaviour in the system:

- **Super-Administrator** manages the rights for other roles and provides application environment settings.
- **Administrator** takes care of the operation of the application. He/she creates new tasks, manages users, assigns patients to therapists, etc.
- **Therapist** assigns patients and gives them neurorehabilitation tasks.
- **Super-Therapist** creates custom tasks that other therapists can use.
- **Patient** role is assigned to each user after registration. The patient performs tasks assigned to him/her and can evaluate them.

4 BrainIn WEB APPLICATION

BrainIn is built on the ASP.NET MVC framework using the Microsoft SQL Server database. Each neurorehabilitation task is implemented in the game framework Unity 3D, providing developers with rapid exercise development and huge graphic variability. All exercise templates are based on a minimal template with basic functionality. It guarantees the same user interface (such as the menu, icons, buttons) through all exercise templates.

There is a landing page for non-registered users with basic information about the project. It allows users to try out sample tasks. For registered users, functionality is different for each role in the system. There is a dashboard control panel with statistics, graphs, and shortcut buttons for quick and easy access to essential features. An example of the dashboard with results is shown in Figure 2.

The BrainIn system is available at https://brainin.kiv.zcu.cz/. Users' recommended requirements are 64bit OS, Mozilla Firefox or Google Chrome web browsers, and a touch screen for fine motor tasks.

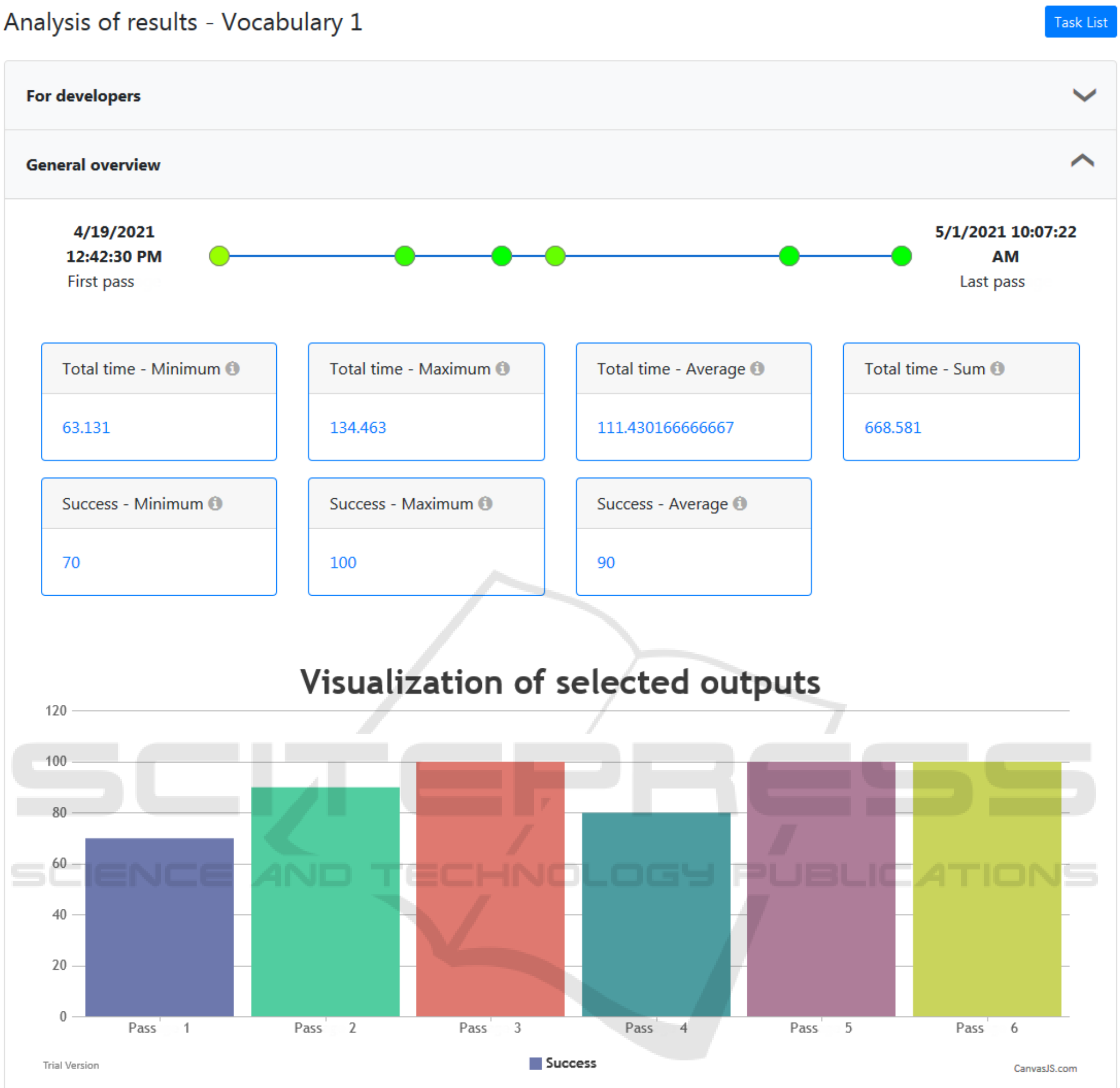

Figure 2: Visualization of results from the Vocabulary task.

4.1 Data Collection and Annotation

The BrainIn system collects anonymized data from the neurorehabilitation process. The aim of the data collection is:

- to provide continuous neurorehabilitation results (i.e., output parameters of tasks) to therapists to personalize therapy,
- to allow export of multiple datasets in JSON format for statistical analysis.

All patients sign the informed consent about anonymous data collection and further processing using a web form. We process the following personal data in the system: name and surname, e-mail address, username, and password.

For statistical processing during system validation and development, we collect and process additional data in Google Forms: Patient ID, gender, age, neurorehabilitation start date, duration of the BrainIn neurorehabilitation in weeks, assigned tasks, patient education, dominant hand, initial patient condition, the patient's final condition, the reason for ending therapy, and the patient's behavioural data.

Table 1: Examples of Default input and output parameters from the Vocabulary template.

Input parameters	
Parameter	Description
Number of rounds	Number of repetitive parts of the task
Number of options	Number of multiple choice fields (one correct)
Shuffle	Whether to show options in random order
Help	How many times help can be used during a task
Showing the right solution	Whether to display the correct solution
Output parameters	
Parameter	Description
Total time	Total run time of the task in seconds
Round time	Run time of each round in task in seconds
Success	Percentage success of the task
Help used	If the help was used in the round

5 NEUROREHABILITATION TASKS

5.1 Categorization of Tasks

The BrainIn system contains samples of publicly accessible neurorehabilitation tasks. Now the system has six task categories (examples of tasks are given in parentheses):

- Speech functions (Text Completion 1, Word Series, Vocabulary, Anagrams, Charade, Characters search, Interview)
- Memory (Ascending Numbers)
- Logical thinking (Lamps, Pyramid, Orion)
- Concentration (Lettuce Harvest, Test Tubes, Addition and Subtraction)
- Spatial orientation (Grid)
- Light motor skills (Finish the Half Example, Painting with Hands, Joining Points, Connecting Pairs)

5.2 Speech Therapy Use Case

Patients with speech disorders, such as aphasia, need speech therapy in addition to classical rehabilitation. This rehabilitation should always be targeted and should reliably lead to speech adjustment. If the patient is hospitalized, they receive this care daily in the hospital. After their release, the patients have to train at home according to the instructions of a clinical speech therapist and a regular speech therapist.

The BrainIn system offers daily targeted speech therapy tasks – tailor-made brain training. These are mainly exercises focused on naming and syntax disorders, disorders of language emotion, memory, attention, reading, analysis, word synthesis, and exercises in text and field of view.

The tasks *Vocabulary* and *Word series* allow the patients to strengthen lexical semantics, vocabulary, and equipment of concepts. Skills such as reading, text orientation, perception of phrases, and understanding of meanings are supported by the task *Text completion*. The *Anagrams* and *Word Charade* tasks help the patients to analyze and synthesize letters (or sounds), syllables, and words and thus facilitate writing. The *Ascending Numbers* task strengthens visual memory and trains arranging consecutive elements.

All tasks require attention and concentration; they can be considered cognitive tasks. The speech tasks are ranked from the lowest difficulty (level 1) to the average difficulty (level 5).

As an example, the task Vocabulary (see Fig. 1) is provided. The patient is asked to select the caption corresponding to the picture shown. Similarly to other tasks, there are yellow control buttons on the right of the screen. The therapist can give the patient systemic help in text form or by hiding 50% of the options. The question mark button is used for this option. The patient can turn on/off all audio stimuli of the task using the speaker button. The vocabulary contains over 400 words, which fall into 16 categories (food, fruit, vegetables, personal things, colours, profession, musical instruments, animals, cities, flowers, trees, transport facilities, buildings, furniture, home appliances, and home accessory).

6 THERAPEUTIC PRACTICE AND RESULTS

Since early 2021 the BrainIn system has been used in hospitals and care homes in the Pilsen region. Four

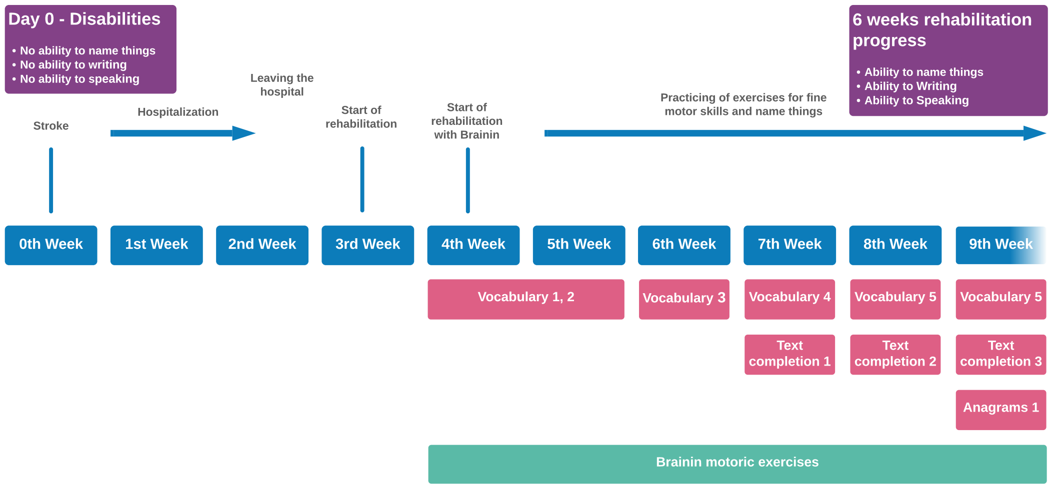

Figure 3: The timeline of patient progress when performing neurorehabilitation tasks with the BrainIn system.

Table 2: Basic patient data.

Institution	Sex		Age	Education			Laterality		Total
	M	F	-	Primary	Secondary	Tertiary	L	R	
University Hospital	3	3	37-64	0	4	2	0	6	6
Zbůch Centre	8	2	27-64	4	6	0	6	4	10
Total	11	5	0	4	10	2	6	10	16

patients (aged 37-49) have been actively performing logopedic tasks, and two patients (aged 49-64) have been actively performing light motor tasks in the University Hospital. In the centre of residential and field social services in Zbůch, ten patients (aged 27-64) have been using the BrainIn system for various tasks. While in this care home patients are generally stable and significant improvements are not expected; in the hospital, the patients' improvements are monitored using various screening methods (e.g., MAST, The Mississippi Aphasia Screening Test (Nakase-Thompson et al., 2002) for logopedic patients and BI for patients with cognitive problems). The basic data about the patients is given in Table 2.

A woman, 48 years old, was hospitalized in March 2021 for a cerebral haemorrhage caused by a brain tumour and underwent urgent surgery. Her initial MAST score was 64/100. She could not write and express what she wanted to say and name one-third of the objects shown. She started to perform neurorehabilitation with the BrainIn system consistently and regularly about one month later. Simultaneously but less frequently, she has been given traditional neurorehabilitation tasks on paper. Her condition, including speech, has gradually improved. Now (December 2021), she remembered 50/50 objects shown, sometimes with a delay. Moreover, her MAST score improved to 83/100 (May 2021) and 88/100 (December 2021). Her progress when performing neurorehabilitation with the BrainIn system is depicted in Figure 3.

7 CONCLUSION

This paper presents a novel online system for personalized neurorehabilitation. BrainIn is based on a close collaboration between therapists and patients and allows a wide range of task parameter modifications. These modifications are individually selected for each patient and are gradually adjusted during the neurorehabilitation process. These adjustments mean that it is difficult to evaluate the benefits of the BrainIn system statistically. Instead, we presented a specific case of the neurorehabilitation process. For future work, once more anonymized data are collected, it is planned to apply machine learning methods to help to personalize the course of neurorehabilitation.

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