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OTDK paper

The effect of the neuroMoon device on cognitive executive functions
through Theta/Beta neurofeedback training

OTDK dolgozat

A neuroMoon eszköz használatnak hatása a kognitív végrehajtó
funkciókra Theta/Beta neurofeedback tréningen keresztül

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1. Introduction

High cognitive performance has never been a bigger asset than in today's fast-paced and competitive environment. Optimizing and achieving peak performance is a crucial part of success in many areas of life, including scientific, academic and business settings. The explosive development of technology in the past few decades has given science a great number of tools to experiment with in an equally great number of areas, one of which is human and artificial intelligence. In recent years, Brain-Computer interfaces have been a widely and thoroughly discussed topic, with its varying use for both clinical and performance-enhancing uses.

This project serving as the topic of the current paper came to life in cooperation of the European Space Agency's (ESA) Business Incubation Program, which supports selected projects working on the development of the pre-mission training of their astronauts. The aim of our project is to develop a neurofeedback application, which can be used for the cognitive enhancement of astronauts of the ESA. Furthermore, the results of this study will provide valuable contributions to the field of neurofeedback.

Objectives of the whole project

1. Developing a neurofeedback device that is able to assist European astronauts with their cognitive abilities during their training.
2. Enriching scientific knowledge about the use of neurofeedback for the improvement of cognitive performance

The application is currently in a testing stage, and it is currently being tested on participants recruited from high-achieving athletes. My paper describes a pilot study prefacing these tests, where the finished application was tested on a small number of participants with slight modifications in the study design in order to fit the requirements for the pilot's purpose.

Objectives of the pilot study introduced in this paper

1. Establishing the neurofeedback protocol
 - a. In order to achieve the desired effect with the training, the main principles of the NFT had to be established. These include the targeted frequency bands, the length,

number and frequency of the training sessions, the type of feedback and the methods based on which we determine whether the training had been successful.

2. Designing the application and interface

- a. Parallel to the neurofeedback protocol, the application was developed. The game itself serves as the visual feedback given to the participants, while calculations run in the background making sure that the feedback is presented in real time, based on the activity in the participant's brain.

3. Testing of the neuroMoon device and application

- a. After establishing the NFT protocol and developing the application, the neuroMoon device was ready to be tested. In the scope of this paper, I conducted a pilot study, pre-testing the application with a small number of participants and a slightly altered testing method.

The structure of the paper follows and describes the project through these three objectives. First, the existing literature on neurofeedback is discussed, based on which knowledge the principles of the neurofeedback protocol of the neuroMoon device were established. After this, the device itself is introduced, including the portable EEG headset and the application, which serves as visual feedback for the training. Finally, the testing of the device is conducted and the results and observations are discussed.

My contribution to the project was as follows:

1. I conducted literature review of prior neurofeedback studies
2. Based on these studies, I assisted with creating the final neurofeedback protocol
3. Adhering to the purpose and target group, I planned the main design principles of the neurofeedback game
4. I recruited participants and conducted the pilot study
5. I analyzed the results of the pilot study and drew conclusions about the necessary changes and recommendations for the final product

2. Neurofeedback

Electroencephalography-based (EEG) neurofeedback training (NFT) is method based on operant learning that can non-invasively influence certain brain activities using real-time feedback based on electrical signals from the brain (Eschmann & Mecklinger, 2022, Viviani & Vallesi, 2021)

2.1. Brain waves

Different brain states and activities are accompanied by oscillations that can be detected in the form of electrical signals with an EEG device. There are several distinguishable frequency bands associated with these activities (Enriquez-Geppert et al., 2014). Targeting these frequency bands with neurofeedback can lead different changes in the activity of the participants' brain, with the goal of improving certain aspects of their lives.

Delta waves (0-4 Hz)

Delta waves are associated with the state of deep, dreamless sleep. (Liu et al., 2016). The delta frequency band, is often targeted through neurofeedback, together with the Alpha band with the aim of treating chronic tinnitus (Jensen et al, 2020).

Theta waves (4-8 Hz)

The Theta frequency band is most often associated with drowsiness, decreasing its power is connected to improvement of cognitive functions and attention (Liu et al., 2016), while decreasing it over beta (Theta/Beta ratio) during awake hours is connected to better memory consolidation (Reiner et al., 2014).

Alpha waves (8-12 Hz)

Alpha bands are associated with a relaxed, awake state. During neurofeedback, increasing individual alpha power can help with memory and visuospatial skills (Liu et al., 2016).

Beta waves (12-30 Hz)

Beta waves are associated with an awake, alert consciousness, as well as a state of emotional arousal (Liu et al., 2016). The Beta frequency band is often targeted in neurofeedback studies

aiming to enhance cognitive performance and even spatial abilities and creativity (Doppelmayr, & Weber, 2011).

Gamma waves (30-80 Hz)

The highest frequency gamma waves are often associated with higher cognitive functions, with the frequency of 40 Hz playing the most important role in brain connectivity (Liu et al., 2022).

2.2. How does neurofeedback work?

As discussed above, mental processes are accompanied by specific brain activities that can be detected in the form of an electric signal. The main principle of neurofeedback is that by monitoring these electric signals, and feeding back this information to the participants, they would be able to learn to control this specific activity of their brain, which would then lead to the effect the training is supposed to achieve.

During EEG neurofeedback, the participant wears an EEG device, which is connected to a computer that analyzes the incoming data. NFT works by influencing either the amplitude or the frequency of a specific band. This shows up as either the increase or decrease of the power of a certain frequency band in the EEG signal. During visual NFT, the participant is told to fixate on a screen, where, according to the activity of their brain, certain events will occur. Whenever the activity of the brain is reflecting the goal of the training, a desirable event takes place. This information, through the visual system, will reach the brain and through the process of operant conditioning, a learning process will take place, where the brain will be more likely to create oscillations in the targeted frequency band.

It is important to note that this process is not necessarily conscious, the participants might not be able to tell what their brain does differently and why positive feedback was given to them. This also depends on the type of training they receive, as for example, when they are given a training meant to promote relaxation, they might be told to try to relax their mind, however, in the case of performance enhancing training programs it is not always this simple. Participants might be told to try different strategies to try to influence the outcome, however, this is rarely a conscious process.

2.3. Developing a Neurofeedback application

Neurofeedback has been broadly tested and used for different purposes, which also means very different modes of application. When developing a Neurofeedback application, there are important things to consider in order to achieve the best result in the area we are applying it to.

In this section I have included both the chosen methods for both the pilot study and the extended study as they differ in important aspects and both are crucial when arriving at the conclusions (*Table 1*).

2.3.1. The purpose

Neurofeedback can be used and has been tested for various purposes. It can be used in a clinical setting, to treat certain disorders like ADHD and different anxiety disorders (Enriquez-Geppert et al, 2019, Tolin et al., 2020). However, it is also often tested outside of clinical uses, often, like in our case, for cognitive performance enhancement (Da Silva, & De Souza, 2021).

The aim of the neuroMoon device is to enhance cognitive abilities, more precisely executive functions of astronauts, which was the focus of both the pilot and the extended study.

2.3.2. Targeted frequency bands

As discussed above, there are different bands that can be targeted, and which one we choose depends on the effect we would like to achieve. For the current application we targeted two bands with opposing effects. The Beta band is associated with concentration and focused attention, so in order to enhance these attributes, we need to increase the power of the Beta frequency band. To enhance these effects, we also targeted the Theta band, which is associated with a state of relaxation. This state is not desirable for our current purposes, so the power of this frequency band needed to be decreased.

The way these two effects can be targeted at the same time is using their ratio for the feedback, where either increasing the power of Beta, the decreasing the power of Theta, or the combination of the two would be a desired effect, and were therefore rewarded during the neurofeedback training. This is called the Theta/Beta ratio, which would need to be decreased or the Beta/Theta

ration, which would at the same time be increased. The Beta band in the experiment is set as 12-15 Hz, the Theta Band is set as 4-7 Hz.

2.3.3. Length of the training

In prior studies we can see a wide variety in the length and number of training sessions. Since there has not been a clearly superior method detected, there is no consensus in the most effective length and number of sessions reached.

In the extended study we are aiming to validate the neurofeedback training by comparing it to an existing method, which operates with a training session of 3x3,5 minutes, so in order to be able to compare the two methods we also chose this amount of time for one session. In the extended study, this session will be repeated 12 times over 4 weeks.

In the pilot study, we tested the neuroMoon device over one single session of 3x3,5 minutes. This means a relatively small amount of time spent with training, which suggests that if there is any result to show, it would be best detectable in the short term, while long term effects would not be expected.

2.3.4. Testing of results

The effects of the training can be measured in two ways. By comparing the baseline EEG data of participants before and after completing the training sessions we can get a view into the actual activity of the brain and see if the power of the targeted oscillation bands has changed significantly in the resting state.

We can also measure behavioral results, meaning that the desired effect has been reached, for example, in our case, an improvement in the executive function has taken place.

In the extended study both results will be monitored and analyzed. The change in the baseline EEG activity of participants will be compared before and after the 4 weeks of training. This method will help us determine whether training was successful and participants were able to alter their brain oscillations. Behavioral results will be measured with the help of the Vienna Testing System (VTS). The VTS was designed to monitor the psychological abilities of high performing athletes

and for this experiment the modules specifically monitoring executive functions have been selected.

In the pilot study, only the behavioral results have been compared. Cognitive abilities were tested through two tests, the 2-back test and the stop-signal test.

2.3.5. Type of feedback

The type of feedback can take different forms, like visual, auditory or the combination of the two. In the current state of the application, we are using visual feedback in a form of a videogame, however, in the later stages an auditory feedback is also planned to be added.

Table 1. Comparing the design of the pilot study and the extended study

	Pilot study	Extended study
Purpose	Enhancement of cognitive abilities	Enhancement of cognitive abilities
Targeted frequency bands	Theta/Beta ratio	Theta/Beta ratio
Length of training	3 x 3,5 minutes (1 session)	12x3x3,5 minutes (12 sessions)
Testing of results	Cognitive tests	Vienna test, analysis of EEG data
Type of feedback	Visual, neuroMoon game	Visual, neuroMoon game

3. The neuroMoon device

The neuroMoon device used for the neurofeedback training consist of a portable EEG headband, and the application that runs on a tablet using the Android operating system (*Figure 1*).



Figure 2 The neuroMoon device in use

3.1. The headband

The neuroMoon headband is a 4 channel, dry electrode, portable EEG device (*Figure 2*). This device is a product formerly developed by the research group and it is currently commercially available to the general public. The device uses Low Energy Bluetooth to communicate with the tablet, which runs the Android application. Thanks to its portability and simple design, the neuroMoon headband can be used in any environment and even without the help of an EEG specialist. This is a key factor in the product's usability, as it is not tied to a specific place or expertise and can be used anywhere, even in space or any other field requiring high cognitive performance.



1. Figure The neuroMoon headband

3.2. The application

The neuroMoon application was the main focus of the current project and was developed by the research group for the purpose of enhancing the cognitive abilities of the high-performance astronauts in scope of the current collaboration with the ESA. In the following section the interface of the application and the design of the neuroMoon game will be introduced.

3.2.1. The user interface

In the application, after logging in, the user can choose from 3 different tabs in the bottom of the screen (*Figure 3A*).

The “**Neuro**” tab allows to access developer tools and the option to go directly to the game (Figure 3A).

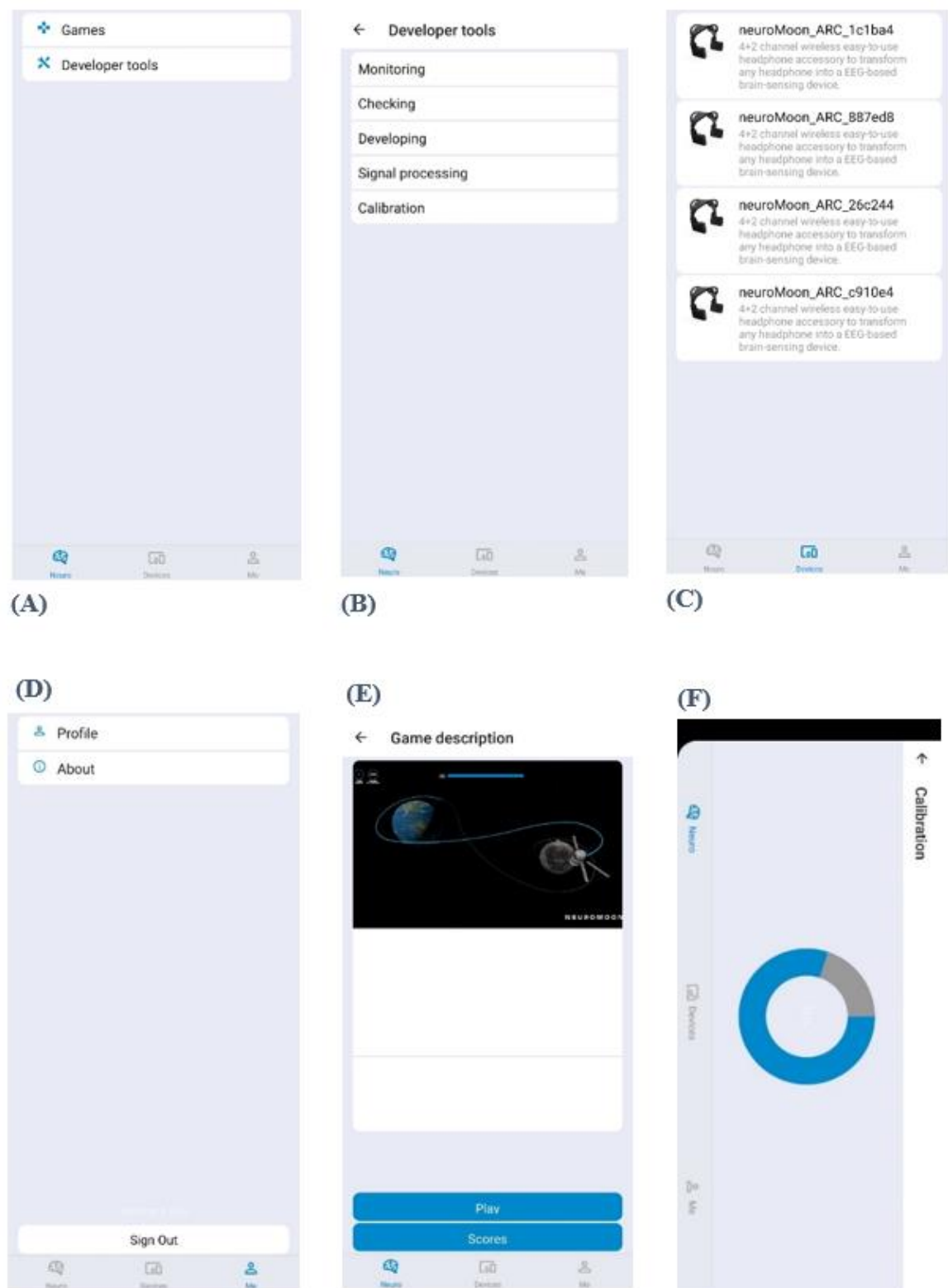
The Developer tools allow for a selection of settings (*Figure 3B*) These settings do not need to be altered by the participant but allow for several modifications and monitoring options to the person responsible for the experiment.

In order to be able to use the application, it has to be connected to the headband in the “**Device**” tab (*Figure 3C*).

The “Profile” tab allows the user to see the details of the selected profile, information about the device and application and also offers the option to log out (*Figure 3D*).

After the device is put on the participant’s head, and connected to the tablet through the “Devices” tab, the game is ready to be played (*Figure 3E*).

After pressing start, the calibration process begins where baseline activity is measured through a 30-second calibration period During this time the participants are instructed to keep their eyes open and look at the loading screen while staying in a neutral mind state, meaning that no concentration or relaxation is necessary. After the 30 second calibration participants the game starts and the training has begun.



3. Figure Screenshots of the user interface of the neuroMoon device

3.2.2. The game

The game displays a satellite orbiting around the Earth and Moon on a fixed path (*Figure 3*). If the neuroMoon device is not connected, the satellite moves in a steady, slow speed, and when the device is connected and the training is in progress, the speed of the satellite serves as the visual feedback for the change in the Beta/Theta ratio. Whenever the Beta/Theta ratio increases, the speed, also increases, while a decrease in the Beta/Theta ratio would lead to a decrease in the speed as well.

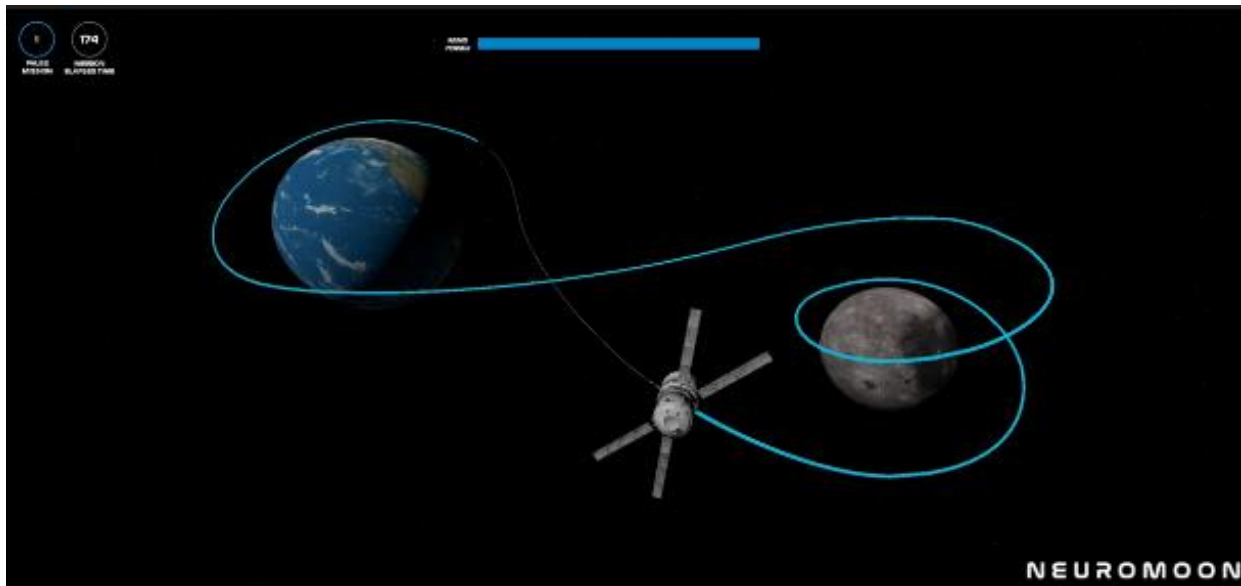


Figure 4 3 Screenshot from the visual feedback interface of the neuroMoon game

The velocity of the spaceship is calculated with the following formula:

$$v = (\text{default_v} * (1 + 2 * (\text{new_value} - \text{calibrated_value}) / \text{calibrated_value}))$$

Where:

- **calibrated_value:** the average density value of a power spectrum of Beta/Theta ratio calculated during the calibration period.
- **new_value:** is the density value of a power spectrum of Beta/Theta ratio calculated during the neurofeedback at a specific time interval.
- **v:** actual speed of the spaceship
- **default_v:** default speed of the satellite

The goal of the game is to increase the speed of the orbiting satellite, which increase can also be followed on the progress bar on top, labeled “Brain Power”

In the upper left corner, the remaining time of the session is displayed under “Mission elapsed time”, which in the pause between sessions is replaced by a timer showing the time remaining until the “Next mission” which refers to the next training block (*Figure 3*).

The goal of this design is to create a familiar atmosphere to the astronauts, where they are also being reinforced and reminded that the training will result in success in their real-life missions. It was also the intention to make the interface as game-like as possible, mimicking the design and objectives of other computer games, to make the training enjoyable, in order to make the training enjoyable through the methods of gamification, instead of using a simpler design, often used in neurofeedback applications, which would be more likely to get boring after a certain number of sessions.

4. The experiment

After deciding on the neurofeedback protocol and developing the application, the pilot study for the testing of the device could be conducted.

4.1. Participants

8 participants took part in the pilot study, 5 females and 3 males, age and medical condition was not controlled for.

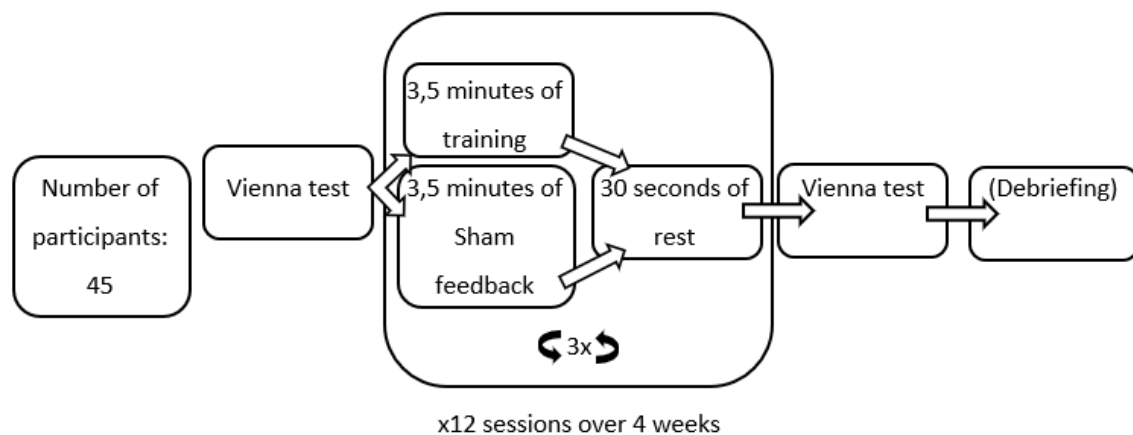
The participants were put in two different groups. The experimental group received normal NFT, while the control group received Sham feedback. Sham feedback meant that the speed of the satellite was pre-set, modeling its movement during an actual NFT session, meaning that the wearing of the neuroMoon device had no effect on the speed at all. The sham-group was used to control for the effect of learning, which is usually present with a great effect at second administration of cognitive tests.

4.2. Protocol

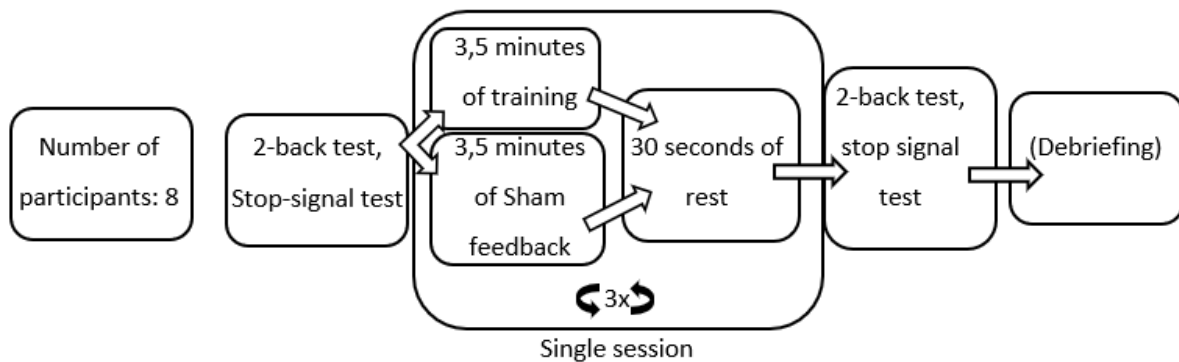
The Protocol consisted of three main steps which were the same in both of the groups, with the difference that when the experimental group received training, the sham group received sham feedback.

1. Cognitive tests (2-back test and stop-signal test)
2. NFT/Sham feedback (3x 3,5 minutes of training with 30 seconds of rest between training blocks)
3. The same cognitive tests administered again

The protocol of the pilot study is visualized in *Figure 5* and can be compared to the protocol of the extended study in *Figure 6*.



4. Figure The protocol of the pilot study visualized



5. Figure The protocol of the extended study visualized

4.2.1. Cognitive Tests

The results of the training were monitored by completing two cognitive tests measuring the several aspects of executive functions of the participants. The two tests were conducted directly before and after the training session. Participants completed a 3-back test, meant to assess working memory, and a stop-signal test, meant to assess impulse control, two abilities part of the executive function. In the case of both tests we monitored two dependent variables, reaction time and accuracy. Data for both tests was collected using the PsyToolkit software (Stoet, 2010, 2017).

4.2.2. Training

After the first cognitive tests, the participants were familiarized with the device and were given a brief on what their aim is and were instructed to try to increase the speed of the spaceship. They were advised to try different strategies on their own and were explicitly told that the aim is to increase the speed, and they should acknowledge that as success whenever that happened.

After this, the device was connected to the tablet through Low Energy Bluetooth and the game was started. The training session consisted of three 3,5-minute-long session, with 60 seconds of rest between them.

After the training, the participants were asked to give comments on how much they felt they could influence the movement of the satellite, and were given an informal debriefing, where they shared their experiences about the training.

4.3. Results

The results pre and post training were compared using a Student's t-test in both groups. In the case of the 2-back test, both by the NFT ($p=0.082$), and Sham ($p=0.19$) group, we could detect a decrease in reaction time (*Figure 6.*)

When looking at accuracy, in the case of the NFT group we could detect an improvement, ($p=0.7$), while the Sham group's performance decreased ($p=0.84$) (*Figure 6*).

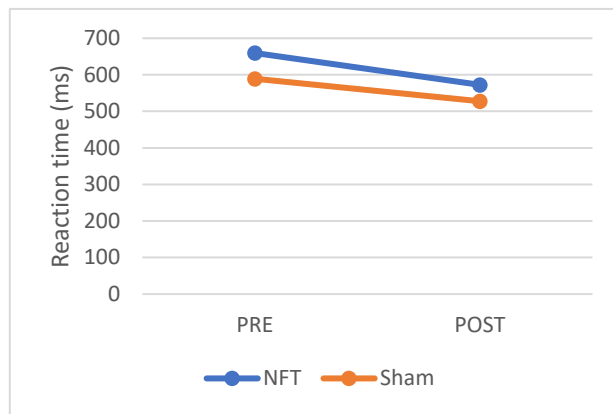


Figure 5 Differences in reaction time of the NFT and Sham groups in the 2-back test

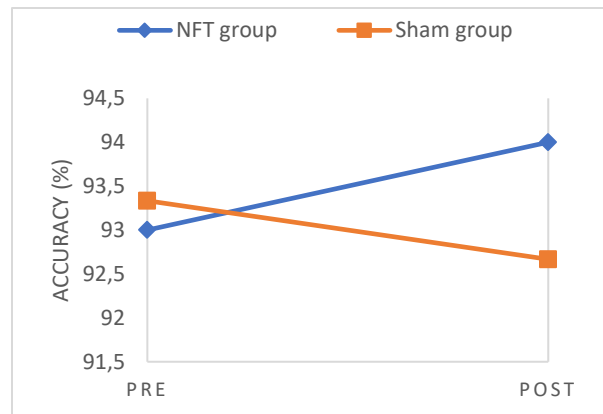


Figure 6 Differences in accuracy of the NFT and Sham groups in the 2-back test

Due to an error at the data acquisition of the stop-signal test, those results could not be adequately analyzed, therefore they will not be included in the current paper.

4.4. Discussion of results

In line with our expectations, the NFT group has achieved better results in both the reaction time and accuracy in the 2-back test. It is surprising however, that while improving in reaction time, the sham group produced worse results in accuracy in the post-training measurements.

The statistical tests showed no significance in any of the presented cases, however this was expected and is partly due to the small number of participants. It is important to note however, that even with this small sample size, the results of the NFT group in reaction time is nearing significance, which gives us hope that with a bigger sample size the tests will result in a significant effect. This could prove what we can only suspect based on this results, that Theta/Beta neurofeedback has a positive effect on working memory, even after only 10.5 minutes of total training time.

The sample size of the pilot study was not large enough to confidently discuss the effectiveness of the application and the effects of Theta/Beta neurofeedback training yet. However, there are some conclusions that we can draw from the experiment, regarding the design of the study.

5. Conclusions

By looking at the objectives set at the beginning again, we can conclude that the project has been successful, and the objectives we set have been achieved.

1. We have created a neurofeedback protocol meant to target the cognitive abilities of astronauts through Theta/Beta neurofeedback.
2. The application has been developed and is currently in its testing phase, while still in need for further development, it can already be used for its intended purpose.
3. A pilot study has been conducted, where I was able to test the neuroMoon device on a small number of participants, which lead to valuable observations and conclusions which can later be applied when the application is developed further.

5.1. Observations

- In the case of the 2-back test, several participants achieved 100% or near 100% in accuracy, therefore a more difficult 3-back test would be more beneficial for future use, so that we can get more sophisticated results.
- The loss of data due to the problem with the administering of the stop-signal test was a big loss, as instead of two, we were only able to analyze change in one cognitive function. This problem shall be investigated and fixed.
- Participants from both the NFT and the Sham group reported during debriefing that they felt like they had no control over the movement of the stimuli. This would be expected from the sham group, however in the case of the NFT group a slight change in the sensitivity of the system might be in order, to give participants a sense of success to encourage them to carry on with the training. However, 3 x 3,5 minutes of training is considered very short in neurofeedback training terms, so in the extended version of the experiment a gradual learning is expected to occur, which also proves that the device is working and that participants are able to gradually change the activity of their brains.
- The sample size was small and was never expected to lead to significant results. In the case of the extended study, 45 participants will take part in the experiment, which should lead to reliable results.

5.2. The future of the project

- The extended test of the neuroMoon device is currently being conducted.
- Based on the results of the pilot and the extended experiment it will be decided whether the main principles of the technology are correct and if so, the product can be developed further and made available for the astronauts of the ESA in 2023. If results are not satisfactory, further modifications will need to be made and the device and application will need to be retested.
- Even after the first version of the device is finished, further development and constant updates will be needed. The game can be extended with different levels of difficulty and design, in order to make the training even more enjoyable, to give users the satisfaction of progress and by increasing difficulty, achieving even better results in cognitive abilities.
- A big limitation of visual feedback is that it cannot, by design, be used during, only before and after the actual activity, for which the enhanced cognitive abilities might be required. This can be solved by adding a secondary audio feedback, through which, the effects of the operant learning can be recalled even when the user is not looking at the screen.

To conclude, we can say that the project is far from over, however the first stages of development have been finished, with the initial test providing promising results. We hope that this project will be a useful addition into the ever-growing field of neurofeedback and that the neuroMoon device will fulfill its purpose of becoming a useful part of the ESA astronaut training's repertoire.

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