IN PURSUE OF A SHORT-TERM EEG NEUROFEEDBACK THEORY: RESEARCH OUTLINE AND FIRST RESEARCH OUTCOMES

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Abstract

This paper presents an overview of the methodological road map constructed to clarify several reoccurring issues in EEG neurofeedback (NF) research, namely the problems with small samples and with a vast multitude of variables. Data, both qualitative and quantitative, from three studies (n=3, n=7, and n=16) and design of two research steps yet to be completed are presented to illustrate our methodological standing point. Furthermore, we aim to explore the usefulness of conceptualizing neurofeedback experience as a "game" in a research context, in contrast to the prevalent "neurofeedback as treatment" conceptualization. Overview of performed and planned research steps relying on mixed methods work with introspective data and EEG recordings as well as suggestions for direction of future research in the field of EEG neurofeedback are presented together with a brief description of an open-source application for neurofeedback practice and research, an application developed to help to build the short-term EEG neurofeedback theory.

Keywords

EEG Neurofeedback, Game, Treatment, Within-Subject Design

1. Introduction

The field of EEG neurofeedback research is very vibrant. Numerous studies and meta-studies have been conducted over the last years and decades (Omejc, Rojc, Battaglini & Marusic,2018; Perl & Perl, 2019), still the field seems to be far from reaching a consensus in numerous crucial aspects (Dagenais et al. 2014; Micoulaud-Franchi et al., 2015; Thibault, Lifshitz & Raz, 2017). Though recent years have seen some activity to establish a cooperative framework, e.g. researchers agreed on a universal neurofeedback research blueprint (Ros et al., 2020), a coherent and widely accepted *theory of EEG neurofeedback* is very probably still far away.

The pioneering researchers in the area of EEG neurofeedback framed the process as operant conditioning of the electrical activity of the human brain. After a wave of initial enthusiasm and a spike in research interest in the area of neurofeedback, this theoretical approach got eroded by numerous inconsistencies in results across different studies (Kropotov, 2016). These incongruencies that keep showing up till today might indicate the lack of specific effects of neurofeedback as a treatment. A recent discussion between Micolaud-Franchi & Fovet on one side and Thibault & Raz on the other (Micolaud-Franchi, Fovet, Thibault& Raz, 2018) reflects the underlying conflict of views. Some researchers are convinced that the EEG neurofeedback works just as good as any other placebo treatment, yet others are stretching out the importance of numerous studies, including those on animal subjects (Wyrwicka & Sterman, 1968; Philippens & Vanwersch, 2010), indicating measurable consistent specific effects of the neurofeedback as a treatment for numerous symptoms. Thus the current research practice (double-blind experiment with the between-group design being considered the gold standard of neurofeedback research [Thibault, Lifshitz, Birbaumer & Raz, 2015]) remains quite fragmented and focuses mainly on proving the specific effects of NF training protocols right or wrong.

We were able to find a handful of studies focusing on various technical and experiential aspects of EEG neurofeedback. Instead of exploring the efficacy of a specific training protocol following researchers aimed to shed light on variables frequently left in shadows by many authors of the major studies in the field. Breteler (2016) mentioned his aim to uncover the role of timing of the neurofeedback reward, designing an experiment in which the reward rate or lack between two feedback points presented to a subject becomes an independent variable. Coenen, Palmen, Jonge & Oranje (2019) designed a study to test if a serious neurofeedback game developed for Neurosky home biofeedback devices has the effect it claims to have if the game helps subjects to increase

activity in the target brain wave band. Kober, Witte, Ninaus, Neuper & Wood (2013) had a look at what mental techniques subjects use to control neurofeedback. Brenninkmeijer (2014) took a deep dive into the world of neurofeedback creating a map of almost countless variables that together form the EEG neurofeedback experience, using the lenses of ethnological research. Strehl (2014) analyzed the role of different learning processes possibly taking place during a neurofeedback session. Nevertheless, the process of the interaction of countless variables, that together form the resulting picture, the EEG neurofeedback experience, seems to remain heavily under-researched.

We assume that one of the reasons behind this situation could be found in the manner in which the EEG neurofeedback is perceived by the majority of researchers, therapists, and clients. Neurofeedback is generally seen as a form of treatment, as means leading to some desirable outcome, as something that takes you from point A to point B, not unlike a pill or a drug. Researchers prefer clinical trial templates and focus on long-term general outcomes of the training, as measurable either by imaging techniques or by standardized psychological instruments, tests, questionnaires.

By default, such a design requires a limited number of quantitative variables as input. Thus, the researchers generally pick only a few variables to focus on and mostly ignore the vast entangled net of the rest (Brennikmeijer, 2013). However, not measuring variables does not mean they disappear and stop influencing the results. Moreover, considering the prevalence of studies with low sample sizes and weak statistical power (Button et. al, 2013), we could, with a certain amount of confidence, state that the majority of research in the field might be heavily influenced by chance and non- conceptualized and unmonitored variables.

Our dissertation seeks to present a slightly different angle on EEG neurofeedback research. It is generally assumed that to get neurofeedback to work effectively, training has to be repeated over extended periods (Ros & Gruzelier, 2010). We would call this approach *long-term neurofeedback*. But if we expect that there will be some measurable, observable difference in an EEG parameter after a number of neurofeedback sessions, should there not be a certain change detectable already in the span of one or a handful of sessions (Aart, Klaver, Bartneck, Feisj & Peters, 2007, Kaplan, 2017)? Thus, even *short-term neurofeedback training* should constitute a valid experience to an interested client, as well as serve as a useful research tool.

If we conceptualize neurofeedback solely as a form of treatment, details of the whole process might easily get out of our scope. But as we take a closer look at it, as if exploring the

process of a game, what we are looking at is a multitude of elements (e.g. brain waves, game parameters, EEG devices) that can influence the game's shape and the player's experience. The neurofeedback is in fact a game, not a pill or a diet. Designing a research project that explores the neurofeedback as a game could overcome certain methodological problems inherent to the studies of neurofeedback as a treatment (Dagenais et al., 2014). From a point of view of a researcher, conceptualizing the neurofeedback as a game widens the frame of research interest. The research is suddenly not only about the effects. The process becomes the object of exploration. This frame is by default much larger, comprising variables such as intervals between feedback signals, sampling frequencies of EEG devices, specific content and goals of each neurofeedback game, or all mental techniques ever used by neurofeedback players. On the other hand, the resulting research can become more systematic, the results can become stronger and less dependent on researchers' basic assumptions about the neurofeedback.

Aart, Klaver, Bartneck, Feisj & Peters (2007) thirteen years ago envisioned a bright future for the neurofeedback. Technical advancements will enable people to train their brain activity from the comfort of their homes, playing elaborated games that naturally enhance intrinsic motivation. Influencers such as top athletes will popularize the neurofeedback so people will follow their example and acquire simple to handle, cheap, reliable EEG devices. The neurofeedback will escape the sphere of alternative treatment to enter the area of common mental hygiene. It will help to prevent the evolution of those same symptoms that today have to be treated by neurofeedback training, pills, or psychotherapy.

Moreover, conceptualizing the EEG neurofeedback as a game helps to take the pressure off the subject. If it is not a treatment, nor a contest, the subject might feel more relaxed during a neurofeedback session. More relaxed and free to enjoy the experience, free to explore the possibilities of a given game or training protocol. Framing the process as a game facilitates ease and encourages the subject to apply a more explorative approach, in contrast with the neurofeedback-as-treatment conceptualization which might suggest a passive role of the subject in the whole process. Framing the process as a task can apply pressure on the subject, as it creates a situation where achievement is expected (Kaplan, 2018).

2. Research Topic and Research Instruments

The term EEG neurofeedback arches over a variety of specific training protocols, each of which usually concentrates on one specific EEG parameter, a specific brain wave activity in a predetermined location on the scalp. Training a subject to voluntarily produce or augment the magnitude of the chosen EEG parameter should eventually bring about alleviation of a specific symptom (Marzbani, Marateb & Mansourian 2016).

In our research studies, we do not work with subjects that would be looking for a specific treatment. The experience with neurofeedback thus converts into a playful act of exploration and experimentation. For that reason, we originally gave a great amount of attention to develop specific neurofeedback software and protocol. The training protocol we work with combines four different standard training approaches into one session. The development of the protocol is described in our two previously published papers (Kaplan, 2017 and 2018). In the software we created for our series of studies, the feedback takes the form of simple sonic games. The games do reflect the progressive evolution of four specific EEG parameters. Each game reacts to one EEG parameter.

Table 1: *NF Games, EEG Parameters and their Sonification*

Game		Electrode Location	Nf Parameter	Sound	Modification	Range	Goal
1	**Pitch Tone Low**	C4	12-16Hz	sin wave tone	pitch	8 steps' chromatic scale (C1 - C2)	make the tone's pitch sound low (C1)
2	**Make More Tones**	C3	16-20Hz	chord	number of tones in a chord	0 – 7	make the chord sound wide
3	**Arpeggiator**	F4	8-12Hz	a looped sequence of tones	number of tones in sequence	0 – 32	make the sequence rich with different tones
4	**Noise**	F3 or C4 (varying across studies)	26-30Hz	white noise burst	low-pass filter	0 - 6 000 Hz	make the noise disappear

Table 1 describes the four games we so far used in the research studies. Each game is driven by a specific EEG game parameter (EGP), has its distinct sonic properties which keep reflecting the momentary value of the respective EGP. Before the first encounter with the game, subjects were told what the game's goal was, what the target soundscape should sound like.

We decided to use both qualitative and quantitative data to capture the context of short-term neurofeedback training in its widest possible extent. To collect the *qualitative data*, insider information about the process of interacting with an EEG neurofeedback interface, we are using the tool of semi-structured interviews. Thematic analysis is consequently applied as a tool for qualitative analysis in concordance with Braun and Clarke (2006).

The *quantitative data* we concentrate on is derived from the EEG parameters that drive the neurofeedback interface. Four distinct brainwave patterns in four different locations on the scalp were picked to drive the four separate neurofeedback games that form our training protocol (Kaplan, 2017 and 2018). Each chosen EEG band relative power is measured during the neurofeedback sessions and recorded as a dependent variable for the purposes of our various research steps.

We collect the EEG data in the form of several numeric variables, mapping the evolution of observed EEG parameters each 15 seconds of every round. For each dependent variable, we have 13 measurements from every neurofeedback round. A session consists of 9 rounds, so we collect 9*13 measurements of every dependent variable across varying conditions for every session. The EEG online processing is made in custom patches written in languages OpenVibe and Pure Data. The pieces of code are to be found at our online repository (Kaplan, 2020).

The combination of several games in one session allows us to use the within-subject design, considering each game a distinct experimental condition. The range of statistical tools differs regarding the goals of each of our research steps. The statistical analysis is performed in programs R, Python, and Atlas.ti.

3. Research Questions and Research Steps

We formulated three basic research questions. Data to provide answers are being collected in a series of three studies. To explore distinct aspects of our research problem, a sequence of five consecutive data analysis steps is being performed.

Even though our research expands over several separate studies, all of them share a very similar structure and various elements are kept fixed across the whole project span. Namely, the quantitative data structure (as the number of measurements described above) remains identical from study to study, to enable the data pooling and performance of partial replication studies. This practice allows us to revisit most of our research questions every time we get new data in a new study.

3.1 Research Design Overview

Our design reflects on and reacts to two issues of contemporary neurofeedback research: We intend to overcome the problem of underestimated sample sizes (Dageanais et al., 2014) by applying a within-subject design whenever aiming to perform statistical analysis. Furthermore, we address the problem of a multitude of non-conceptualized variables usually left out of researchers' scope by applying the exploratory and qualitative approach (Ravitch & Carl, 2014).

The following table offers an overview of the most important dissertation research steps currently in different stages of execution. Before the listed studies, we performed a pilot study (Kaplan, 2017), as well as two studies that had to be stopped in the phase of data collection due to issues with the quality of EEG data collected. One of those was an experiment with different forms of EEG sonification, the other being a case study of EEG neurofeedback gameplay with an experienced meditator.

Table 2: *Overview of the Research Design*

Data Analysis Step	STEP 1	STEP 2, 3, 4	STEP 5
Study Scope	**Short-term EEG NF as a game**	**Interaction of players with EEG NF games**	**Game strategies to learn to control specific EEG game parameters**
Sample	7 male musicians	16 students of psychology	20 students of psychology
Study Type	exploratory	exploratory and explanatory	Explanatory
Data Type	qualitative	qualitative and quantitative	qualitative and quantitative
Research Instruments	3 EEG NF games, semi-structured interviews, thematic analysis	4 NF games, semi-structured interviews, thematic analysis, statistical analysis of quantitative and mixed data	3 NF games, statistical analysis of EEG-derived dependent variables and NF game factors, supplementary interviews
Status	performed, published	data collected, the preliminary analysis performed, results and further analysis pending	study to be performed

Outcomes	validation of the concept of NF as a game, creation of the concept of game controls,	list of significant relations between EEG parameters and game variables, list of influential game controls	list of accepted and refused hypotheses about short-term NF training

3.2 Is the Short-Neurofeedback Experience equivalent to the Experience of Playing a Game?

Our first research question targets the validity and usefulness of our conceptualization of neurofeedback, and thus could be articulated as follows: Can we assume that the interaction with the EEG neurofeedback system has the properties of a game (Kramer, 2000)? Is the experience of playing a simple neurofeedback game, driven purely by brain signals, comparable to the experience of playing any conventional game, driven by body movements or commands on the keyboard?

3.2.1 Step 1

We performed an exploratory study on seven subjects to target this question (see Kaplan, 2018). Each of the subjects interacted in a span of one to three sessions with our set of neurofeedback sonic games. Subjects were encouraged to find their way to control the shape of the feedback sound. An interview followed each session. All interviews were searched for recurring motifs and themes that would reflect the experience of interaction with the neurofeedback games. Namely, the strategies that subjects applied to get control over game elements or to achieve the game goals.

The thematic analysis coding resulted in a list of strategies that different players applied, with differing amounts of success, to achieve the specific game goal. The following table lists all identified strategies, e.g. *game controls* – ways to interact with the neurofeedback games.

Table 3: *Game Controls*

GAME CONTROLS / GAMES		Pitch tone low	Make more tones	Arpeggiator
Body Movements	contracting muscles		+	
	closing eyes	+	+	+
	opening eyes		+	
	breathing	+	+	+
Different Levels Of Activation	falling asleep	+	-	+
	getting calm	+		+
	getting activated		+	
	getting stressed	-	-	-
Direction Of Attention	looking inwards	+	-	

	looking outside	+	+	
	switching perspective		+	
Interaction With The Sound	delving deeply into it	+	+	+
	forgetting it	- +	+	+
	sound is just feedback	- +	+	+
Thoughts That Change The Mindset	performing mental tasks	-	+	
	imagining			+
	contemplating memories			+
	deliberate thinking	-	+	
	emptying the mind			
	thoughts out of control	-	-	-
The Flow	associational streams			+
	feeling of flow	+	+	+

Table 3 lists the game control families, such as *body movements*, that were formed merging similar individual game controls, such as *closing eyes* or *contemplating memories*. In the right part of the table, the three columns indicate the subjectively perceived influence of the given game control over the individual games, plus standing for the desired direction of influence, achieving the game goal with the game control, while minus stand for the opposite. Therefore, the plus sign next to a game control name indicates that at least one subject on at least one occasion used this game control to positively influence the game's soundscape. The minus sign stands for the opposite experience. The appearance of both signs in the column indicates that a given game control has had mixed effects over a specific game. It either worked differently for one subject on different occasions, or different subjects tried that strategy and one felt that it led to success while the other felt exactly the opposite effect. Note that table 3 was previously published in Kaplan, 2018.

Two of the 22 different game controls appeared to have the power to influence all the games. No matter what specific EEG parameter drove the game, applying this game control would have the desired effect. When the player achieved a state of mind referred to as 'flow', the game seemed to react desirably, rewarding the player and thus helping her to stay in the very state of flow, that originally helped her achieve the game goals. It was the mental set described as a clear mind, neither fully focused nor unfocused, that was spotted by several players as correlating with the success in the game. On the contrary, when the player found herself wondering about mindlessly, with 'thoughts out of control', thoughts running through her consciousness, the game

seemed to react in an undesirable way, indicating to the player that she is far away from reaching the goal of the specific game.

Except for one player in one session, there was an overall feeling of at least partial control over the shape of the sonic games. As frequently recalled and reflected in follow up interviews, there were moments of approaching the game goal and moments of getting further from it, moments of losing it. Just like when one tries to learn to play tennis. The variety of strategies to control the feedback shape as well as the curiosity sparked in our subjects during the sessions, as manifested in the interviews, both indicate that framing an EEG neurofeedback session as a simple game might have promising results.

3.3 Is it Possible to Establish a Meaningful Interaction with the Neurofeedback System throughout no more than Several Sessions?

Based on the results of research step 1 we drew a sketchy map of the neurofeedback-as-a-game territory. Further questions could consequently target more specific aspects such as the role of game elements, distinct EEG derived game parameters, and different game strategies, controls, and actions.

To get to a more detailed, reliable, and specific description of our games and training protocol, we performed two consecutive studies with nearly identical designs. Samples of 6 and 9 psychology undergraduates got five sessions of neurofeedback. The third and fifth sessions were followed by a semi-structured interview.

3.3.1 Step 2

To figure out whether the games we are using in our protocol are working as expected, whether the players can reach the game goals of each of the four games, we performed a statistical analysis of EEG data gathered and preprocessed during the neurofeedback sessions. The EEG parameters that drove the games were considered our dependent variables, the four games that form our neurofeedback protocol were our experimental conditions. The whole study had a within-subject design (each player got to play every game many times, generating numerous data points), thus we were able to perform statistical analysis with reasonable statistical power despite the size of our sample.

Up to date, we performed an analysis of the data acquired in the first of the two consecutive studies. These were recorded using a modified Emotiv Epoc device with golden cup electrodes

positioned on C4, F3, and F4 locations according to the 10-20 system. The EEG parameters to drive the neurofeedback games were obtained through a series of processing steps:

- Filtering to get an absolute power in a specific band

- Squaring the power

- Windowing the squared absolute power

- Calculating inter-parameter ratio (the ratio between the target band power and the sum of the three remaining game parameter powers) to control for artifacts and excessive inter parameter correlation.

Statistical analysis was performed to figure out if each of the four games facilitated an increase in the power of the EEG band that drove the specific game. In other words, we hypothesized that power in a specific band will increase during a specific neurofeedback game.

- SMR power registered by the C4 electrode will increase during Pitch tone low game.

- Beta C3 power will increase during the Make more tones game.

- Alpha F4 power will increase during the Arpeggiator game.

- EMG C4 power will decrease during the Noise game.

Paired t-tests were performed to test the set of hypotheses. The true mean difference between the specific EEG power during the target game (e.g. the SMR power on C4 during the Pitch tone low game) and the remaining three games were explored. To match the length of two series of data points recorded to test our hypotheses we calculated an average of the EEG power across the three non-target games for each time point of every session.

The results of the analysis indicate that three of the four NF games we used in this study work in the way they were constructed to do. In those three games (Pitch tone low, Make more tones, Noise) players were able to control their EEG activity with the help of the sonic feedback.

Table 4: *Games and their influence on EEG band relative powers*

EEG Band/Game	Pitch Tone Low	Make More Tones	Arpeggiator	Noise
SMR C4	**0.01637**	*NA*	*NA*	0.008732
Beta C3	*NA*	**0.11114**	-0.02622	-0.06723
Alpha F4	-0.04499	-0.53954	*NA*	*NA*
EMG F3	*NA*	0.151004	-0.01661	**-0.1151**

Table 4 lists differences in means of relative powers in observed brainwave bands (alpha, SMR, beta, and EMG) during different conditions – the distinct neurofeedback sonic games. NA's stand for mean differences with $p > 0.05$.

Such information, which games have significant relationships with which EEG parameters, is crucial in two ways: to direct the further development of the games, and to single out those EEG parameters whose further research should be promising.

Further work with quantitative data will center on an exploratory analysis of the intercorrelation of distinct EEG bands within and across the different conditions and games. Different ways to conceptualize success in the game, e.g. different indicators of decrease or increase in one of EEG parameters that interact with the game, are being assessed.

3.3.2 Step 3

Thematic analysis was performed to identify the game strategies, the game controls that our subjects used to achieve specific game goals, to manipulate the sound of the neurofeedback games in the desired way.

Up to date, only partial analysis from data from the first of the two studies has been performed, delivering a list of 22 identified game controls. Some of those were identical to those used by players from our previous study (e.g. closing eyes, getting calm), some of the strategies were original. The 22 strategies, some of them used by more subjects, some of them just by a single one, were grouped into six families: *body movement, calmness, focus, thoughts, imaginations, memories.* These six families of controls cover the whole ground of possible actions a player can take to influence the EEG neurofeedback game.

Data from the second study will be analyzed in a similar fashion. We will code the interviews for each player's interaction with the game. The game control families, the groups of possible game actions listed right above, will be revisited and reevaluated in the context of new motifs identified.

3.3.3 Step 4

This research step yet to be performed, will work with the outputs of two previous steps. Having identified relevant EEG game parameters (Step 2) and having constructed a comprehensive list of players' strategies (Step 3), we shall be able to analyze the nature of their relationship. We will approach this mixed data with a question: which strategies look promising?

We will analyze the performance of each subject over the course of the five sessions, as expressed in the evolution of relative power in observed EEG bands across the different games. Analysis of variance with target EEG band power as a dependent variable and the game type and session number as factors should help to pinpoint the specific occasions in which a subject was able to control the specific game. Alternatively, we might visually inspect the so-called learning curve to identify the subjects that were able to interact with the specific game to successfully reach the game goals (Kaplan, 2017). As a result, we shall be able to figure out which players performed better at general, as well as in which specific moments (what game round and what session).

Once a successful player is identified, we can have a look at the strategies or game controls she chose to control the specific game on a specific occasion. Through this process, we shall be able to assign a numeric value to each strategy. Every time a specific technique will be identified as successful for a subject, a point will be added to generate a numeric value that will eventually indicate its usefulness. The more occasions that the strategy would have led to success in the game, the higher the number. The output of this step shall be a table not dissimilar to the List of game controls (see Table 2 from Step 1). Only the pluses and minuses will get replaced by the newly created numeric indicators of usefulness or effectivity of every given strategy.

3.4 Is there a Universal Way to Learn to Control the EEG Game Parameters?

Up till this point, we always encouraged our subjects to choose or invent their ways to achieve the game goals, to find their strategies. Consequently, we were able to list those (Steps 1 and 3) and to assess how useful each of them gets (Step 4). The last research step of our dissertation is designed to find out if the strategies that have proven useful for one player could be successfully applied by another. Would that what works for one person work for someone else?

3.4.1 Step 5

An experimental study having a within-subject design will be performed. We would gather a sample of approximately twenty subjects (undergraduate students of psychology, to match our former sample). Each of them will participate in five sessions of neurofeedback. Each session will be followed by a short interview.

During one session, every subject will be asked to play three different NF games (each game repeating three times a session and lasting three minutes). During each repetition, a subject will be assigned a different strategy to play the game. Every strategy will be accompanied by written instructions on how to achieve it. The final list of strategies (three per game) will be derived

from the results of the mixed-method evaluation of the usefulness of game strategies performed during the research Step 4. Descriptions of each strategy that will summarize the experience of the players that successfully used those before will be handed out to subjects in written form before each NF round.

For the purposes of statistical analysis, the type of game strategy will become a within-subject factor variable. Consequently, we shall be able to observe the influence of a specific game strategy over a resulting EEG image. The EEG image will be conceptualized as a value of the three EEG game parameters being fed back by the respective games.

The three neurofeedback games will be chosen based on the results of the statistical analysis of previously gathered data (see Step 2). A set of nine hypotheses will be formed, each one targeting a relationship between a specific game and a specific game strategy.

Table 5: *List of Hypotheses*

Variable	Values	Type
Game Strategy	A 1-3, B 1-3, C 1-3	within-subject factor
Game Type	A, B, C	within-subject factor
EEG Parameter	α, β, δ	dependent variable

Example Hypothesis: Game strategy A1 enhances performance (EEG parameter α) in-game A.

The analysis of variance (input of the analysis being the variables listed above in Table 4) shall provide a suitable tool to confirm, or not, each of our hypotheses.

The design of this experimental study is still under elaboration, currently, we contemplate the idea of adding several more experimental conditions. For example, the game design could vary in specific games, the EEG game parameter being expressed through two different modalities (sound or picture) in distinct rounds. This design could help us assess the effectivity of the sonic feedback as compared to the visual. Part of the research sample could as well be gathered from the participants of our previous studies. We would gain one extra between-subject factor, the previous experience with neurofeedback, to explore. Nonetheless, the addition of more variables might damage the statistical power of the study, thus these options still would have to be carefully contemplated.

4. Expected Outcomes

Our research design heads towards a relatively ambitious goal. It should provide a solid base to formulate *a theory of short-term EEG neurofeedback*, to form a neurofeedback framework that would have both practical and theoretical uses. The combined results of all the research steps described above will provide us with a small database. Based upon the analysis of our data we shall be able to generate several statements about short-term neurofeedback, about neurofeedback as a process of playing games with the brain as an instrument and different mental states as game controls.

The theory should indicate which EEG parameters seem to be more prone to come under the voluntary control of a player than others, which particular strategies of interaction with a specific game seem to be universal, useful for a variety of players, and which mental sets and mental actions seem to disrupt the act of playing the neurofeedback game. We shall be able to infer if it is better and more fruitful for each player to search for specific personal strategies, or if it is more useful to apply game controls already developed by other players.

Our theory should be breakable into a set of separate hypotheses that can be tested in the future by adapting or replicating specific steps from our research design (Meehl, 1967). The theory should serve as a starting point in developing new hypotheses that would reflect our research approach and consequently lead to every time more refined theory.

As we duly collect the so-called *insider information*, the introspective experience of our subjects, all through the research steps, we have already been able to address a number of issues that have surfaced during the data analysis phase (Jack & Roepstorff, 2002). Our database of interviews with every subject is there for us to consult on any specific question that might surface. When we discover that a certain game does not work as a priori expected (e.g. there is no statistically significant influence of the game over specific EEG parameter), we can access the qualitative data with a particular question in mind and just code for the possible causes of why this particular game does not work regarding the experience of the players. Quite often we are able to find some possible reasons or causes behind the phenomenon. Coding for reasons behind incongruency in our theoretical expectations and results of quantitative analysis can provide us with a new hypothesis. A new hypothesis can consequently form a part of the theory, or specific practical steps can be taken to improve the protocol or individual games before the next study takes

place. The purely quantitative design would leave such questions unanswered and problems unaddressed, as it simply does not offer the necessary tools (Creswell, Piano Clark, 2007).

The integral "by-product" of our theoretical and research work is the development of the research instrument we used in every step of our project. The *EEG neurofeedback sonification software* is being gradually reworked and expanded, as our project reaches new insights and conclusions, to best suit its purpose. This set of tools (to find up to date public version visit Kaplan, 2020) was created and is being improved with several objectives in mind:

- Providing tools for sonification of the brain signal
- Generating comprehensive information about EEG and neurofeedback games
- Facilitating entertaining neurofeedback experience
- Providing a fully customizable environment

5. Wider Implications

The theory of short-term neurofeedback, or neurofeedback as a game, should provide NF practitioners with basic information highly useful in their therapeutic practice. For one, we shall be able to observe which EEG parameters take longer to acquire control over than others, given a big enough data set. This information can be essential for a neurofeedback therapist, as she can consequently evaluate the progress of her clients more accurately. We will be able to observe which game mechanisms, which shapes of feedback, are more likely to induce a steeper learning curve in a player. Again, this information is very valuable to a therapist who thus does not have to rely solely on her personal experience with the different games or on the client's preferences. Moreover, we shall be able to observe what interactions between specific game settings and EEG parameters lead to desired outcomes, helping players to reach the game goal.

Let us assume that a specific sound in combination with a specific feedback mode is more likely to facilitate the process of getting control over a specific EEG parameter. There is a huge number of game parameters in our software, so devising a controlled experimental study to observe each interaction of distinct variable, element and parameter would be close to impossible. A series of studies each hypothesizing about the interaction of three variables would span over decades if it were to be performed by a single researcher. As the interactions between separate game parameters and distinct EEG parameters most probably have very small effect sizes, so a considerable number of subjects would have to join each separate study (Sullivan, Feinn, 2012).

This explanatory approach focusing on one problem at a time requires designing many smaller individual studies. One study with exploratory character would require impossible amounts of subjects to achieve reasonable probabilities of not being false positive (Luck & Gaspeline, 2017). The collaborative research using unified software that duly records all of the EEG neurofeedback variables in a standardized format should overcome many limitations of the current one-study at a time approach (Curran & Hussong, 2009; Moustafa et al., 2018; Perrino et al., 2013).

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