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BREAKING OUT OF THE FEEDBACK LOOP: TRANSFERRING MASTERY OF SELF-REGULATION DURING NEUROFEEDBACK TO OTHER CONTEXTS

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ABSTRACT: One important question in neurofeedback (NF) research is the mastery of self-regulation and the generalizability of the NF training results. Here, we investigated whether NF users can voluntarily increase the Sensorimotor Rhythm (SMR, 12-15 Hz) activity during repeated NF training sessions while receiving visual feedback and if they can also increase SMR during subsequent transfer sessions without any feedback. We also assessed the used mental strategies during the sessions. Nine healthy adults received real feedback, nine received sham feedback. Only the real feedback group was able to linearly increase SMR within the six NF training sessions. However, they could not increase SMR during the transfer sessions. Participants reported multiple different mental strategies during NF training as well as during transfer sessions with different success rates. These results indicate that participants were not able to transfer successful mental strategies to other situations after six sessions of SMR-based NF training.

INTRODUCTION

In neurofeedback (NF) applications, users can learn to voluntarily modulate brain signals, in most cases the electrical brain activation recorded with the electroencephalogram (EEG), in a desired direction through real-time feedback. The aim is to intentionally reinforce EEG patterns that are associated with optimal cognitive or motor processes. Successful NF training can consequently lead to cognitive, motor, or affective improvements [1]. However, long-term effects of NF training or transfer effects are hardly investigated [2].

Users have varying degrees of success in regulating their own brain activation during NF training. Up to 30% of NF users are so-called non-responders and the exact reasons for this inability are still open [3]. The mental strategies used appear to be an important predictor of the success of NF training. In SMR-(12-15 Hz) based NF training studies, it turned out that participants report many different mental strategies during NF training with different success rates [4-6]. The use of no specific mental strategy seems to be advantageous to upregulate the SMR over central brain areas [6]. But there are also other successful mental strategies reported to increase SMR activity during NF training [4-6].

In this context, the question arises as to whether NF users can transfer mental strategies that they use during NF training to increase SMR to other situations where they do not receive real-time feedback via NF training. In theory, learning how to up-regulate SMR at a given time, which should lead for instance to improved cognitive performance [1, 7], should be transferable to other contexts (e.g., school, work) without real-time feedback of one's own brain activity [8]. In the present study, we investigated the ability of NF users to increase SMR during NF training receiving visual feedback of SMR changes as well as subsequent transfer sessions without any feedback of one's own brain activity. Additionally, we assessed the used mental strategies during NF training and the transfer sessions to see whether the same strategies lead to an increase in SMR in both NF and transfer sessions, or not.

Gruzelier [2, pp. 18] mentioned in his review article that the ultimate goal of NF training is the *mastery of self-regulation* and that this can be evaluated using transfer trials where the participants do not receive any feedback or reward. Such transfer trials are generally included in slow cortical potentials (SCP) NF training (e.g., [9]). However, a differential process analysis is lacking. For instance, Gevensleben et al. [10] included transfer trials without contingent feedback in their NF protocol and also gave home-work. NF users were required to practice their focused mental state, which they should achieve during NF training, at home. However, NF training results or changes in EEG activity during transfer trials were not reported [10]. In a SCP-based NF study by Barth et al. [11], EEG activity during transfer trials were reported. However, as in the other SCP NF studies using transfer trials, no feedback was presented during the transfer trials but participants received reinforcement following the transfer trials in case they had regulated in the desired direction often in form of a smiley. The authors used the transfer trials to categorize the NF users in learners and non-learners. Changes in SCP during NF and transfer trials were not directly comparable [11]. Kleih-Dahms et al. [12] reported SCP results of single subjects for NF and transfer trials. It turned out that in some NF users, SCP changes were not present in transfer trials while in other users, SCP changes were even stronger during transfer trials than during NF trials. In this study, mental strategies during SCP regulation were assessed as well. However, they did not differentiate between mental strategies used during NF and transfer trials [12].

In the present study, we investigated changes in SMR activity during repeated NF training sessions as well as

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in subsequent transfer sessions. We also assessed the used mental strategies during NF training and transfer trials. To rule out possible placebo or unspecific effects [13,14], we also included sham control groups receiving fake feedback. We expect that the real feedback group should be able to increase SMR activity during NF training, while the sham group should not show linear increases in SMR activity. In line with previous NF studies, NF users should report many different mental strategies with different success rates during NF training [4-6]. According to previous SCP-NF studies [11,12], there might be differences in changes in EEG activity during the NF and transfer trials.

MATERIALS AND METHODS

Participants: Eighteen participants were randomly assigned to two groups. One group received real feedback of their own SMR activity (N = 9, 5 females, average age = 25.7 years, SD = 3.02), one group received sham feedback by receiving feedback of another participants' EEG recording (N = 9, 5 females, average age = 22.8 years, SD = 2.96). All participants signed a consent form. The study was approved by the ethics committee of the University of Graz, Austria (GZ. 39/9/63 ex 2019/20).

Design and procedure: All participants performed in sum 9 sessions on different days within 3 weeks. The first session was an instructional session where participants should be relaxed but mentally focused but did not get any visual feedback of their brain activity. In session 2 to 7, NF training was performed. Participants of the real feedback group received feedback of their own SMR activity (12-15 Hz) over Cz via visual feedback. The sham group saw the same visual feedback screen but the movement of the visual feedback was not related to their own brain activity. It showed changes in SMR activity recorded in another participant. The last two sessions were transfer sessions. In these sessions, participants should try to reach the mental state they had during the NF training sessions without getting any visual feedback. Session 8 was performed directly after the last NF training session, session 9 one week later.

Neurofeedback training: During NF training, participants received visual feedback. Changes in target EEG activity were depicted by vertically moving bars. Three bars were depicted on a conventional computer screen. The bar in the middle of the screen depicted changes in SMR (12-15 Hz) power. The bar on the left side of the screen showed changes in theta (4-7 Hz) power (to control for eye movement artifacts) and the bar on the right side of the screen depicted high beta (21-35 Hz) power (to prevent the participants from producing too many muscle artifacts). Per NF training session, 7 three-minute runs were performed. The first three-minute run was a baseline run. Here, participants were instructed to relax and watch the moving bars without trying to control them. This baseline run was used to define individual threshold values per participant (median SMR value for middle bar, median + 1 SD for theta and beta bars). The subsequent six runs were feedback runs where participants were instructed to increase the size of the middle bar while keeping the bars on the left and right as small as possible. An increase in EEG power led to an increase in size of the bar and vice versa. When the SMR bar exceeded its threshold and theta and beta bars were below their thresholds, the bars turned green, and a reward counter increased. Otherwise, the bars turned red. Participants were instructed to be physically relaxed and mentally focused and concentrated to increase SMR activity. This NF protocol has been successfully used in previous NF studies to increase SMR while controlling artifact activity (e.g., blinking, muscle activity) [5-7].

EEG recording and analysis: 12 EEG electrodes were recorded (F3, Fz, F4, C3, C1, Cz, C2, C4, CPz, P3, Pz, P4) using a g.USBamp 16 channels standard amplifier (g.tec, Austria). A linked mastoid reference was used, the ground was placed at FPz. Vertical and horizontal EOGs were placed on the outer canthi of the eyes and superior to the nasion. Impedances were kept below 5 kOhms for the EEG electrodes and below 10 kOhms for the EOGs. EEG signals were digitized at 256 Hz and filtered with a 0.5 Hz high-pass and a 60 Hz low-pass filter. To analyze the EEG data, the Brain Vision Analyzer software (version 2.2, Brain Products GmbH, Germany) was used. Ocular artifacts such as eye blinks were corrected using an automatic ocular correction method (Gratton & Coles), followed by a semi-automatic artifact rejection (criteria for rejection: >50.00 µV voltage step per sampling point, absolute voltage value >±150.00 µV, lowest allowed activity in 100 ms intervals: 0.5 µV, maximal allowed difference of values in 200 ms intervals: 200 µV). All data points with artifacts were excluded from further EEG analysis. Absolute SMR power values recorded over electrode position Cz were extracted by means of complex demodulation (Brain Products GmbH, 2009). Power values were averaged per run.

Mental strategies: To assess the mental strategies the participants used to modulate SMR in the desired direction during NF training as well as during the transfer session, participants had to write down the mental strategies used after the first and the last NF training session as well as after the last two transfer sessions. The verbal descriptions were classified by two independent raters in different categories in accordance with prior studies [4-6]. The categories were: Visual (focusing on visual things, e.g., visual properties of the feedback screen), Cheering the feedback bars on, Breath (concentration on one's own breathing), Auditory (thinking of auditory stimuli), Concentration, Body (focusing on one's own body or bodily sensations), Relax, Cognitive (e.g., mental calculations), No Strategy (reporting to have no specific strategy, to do nothing in particular), Other Strategies. Inter-rater reliability was sufficiently high (across all categories: Kappa = 0.6). Participants reported generally multiple strategies during the sessions.

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Statistical analysis: To define successful NF training performance, we analyzed changes in SMR power within NF training sessions across feedback runs. This is in line with prior studies showing changes in SMR power within NF training sessions but not between training sessions (e.g., [7]). A linear increase in SMR power across NF runs within a training session is an indicator for successful voluntary up-regulation of SMR activity at a given time and voluntary phasic EEG changes, which does not necessarily be related to changes in tonic or background EEG measures indicated by SMR changes across sessions [1,7,15,16].
Hence, to quantify NF training performance, we performed linear regression analysis with SMR power as dependent variable and NF run number (averaged across all NF training sessions) as predictor variable for each participant. The resulting regression slope was used as indicator for NF training performance. A positive slope is a sign of a linear increase in SMR power across NF training runs, while a negative slope is a sign of unsuccessful training. These regression slopes were then compared to zero using *t*-tests against zero per group. Alpha (0.05) levels were adjusted using Bonferroni correction, normal distribution was given.
Furthermore, *t*-tests were used comparing average SMR power across all NF sessions with average SMR power of the transfer sessions (session 8 and 9).
To analyze the mental strategies descriptively, we calculated the percentage of participants reporting a specific strategy per session, averaged over the classification results of both raters. Then, we calculated the average regression slope (changes in SMR power over the runs within a session) per reported mental strategy to determine which mental strategy was associated with a successful or unsuccessful SMR increase and if successful mental strategies during NF training were also successful during the transfer sessions. Note that we only report on the mental strategies used by the real feedback group.

RESULTS

In a first step, we analyzed changes in SMR power within NF training sessions. The real feedback group could successfully increase their SMR power over the NF runs within the NF training sessions. Comparing the slopes of SMR power across the feedback runs against zero showed a significant difference for the real feedback group ($t(8) = 3.20$, $p = 0.01$) but not for the sham feedback group ($t(8) = 0.32$, $p = 0.76$) (Fig. 1).
During the transfer sessions (Fig. 2), neither the real feedback group ($t(8) = -0.90$, $p = 0.40$) nor the sham feedback group ($t(8) = 0.45$, $p = 0.67$) showed a significant linear increase in SMR power across runs. Absolute SMR power across the NF sessions was numerically higher in the real feedback group than in the sham feedback group and higher during the NF training sessions than during the transfer sessions (Fig. 3), but there were no statistically significant differences.

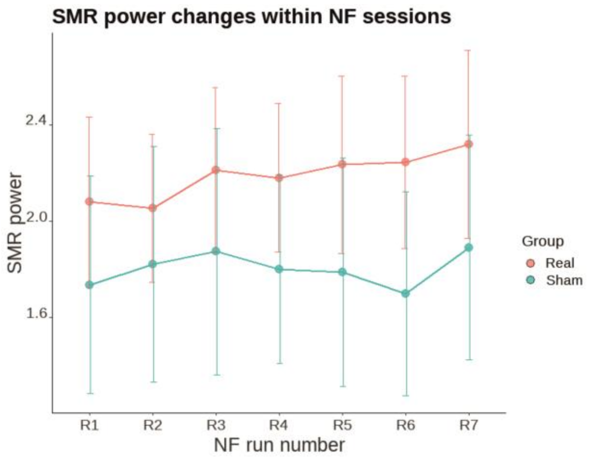

Figure 1: Mean changes in SMR power [µV^2] per group across feedback runs within NF training sessions. Error bars show *SE*.

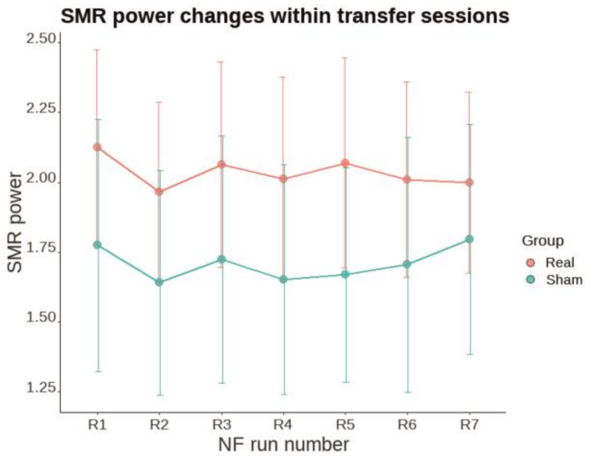

Figure 2: Mean changes in SMR power [µV^2] per group across runs within transfer sessions. Error bars show *SE*.

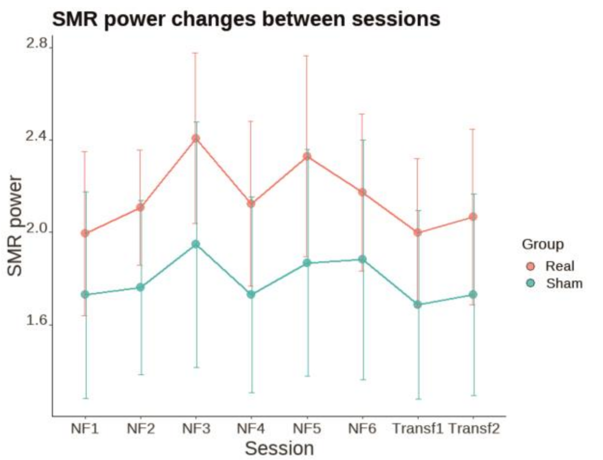

Figure 3: Mean changes in SMR power [µV^2] per group across sessions. Error bars show *SE*.

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The analysis of the mental strategies revealed that participants used many different strategies during the NF training sessions as well as during the transfer sessions (Fig. 4). Across all sessions, Concentration was mention most often, followed by Cognitive and Visual strategies. The frequency of the usage of a specific strategy changed over sessions, but in many cases, the strategies were more frequently used during the NF sessions than during the transfer sessions (e.g., Visual, Cheering, Auditory, Concentration, Relax). The breathing strategy was more frequently used during the transfer sessions compared to the NF sessions. This mental strategy turned out to be the most successful one during NF training indicated by positive regression slopes. However, this strategy was not successful during the transfer session as shown by negative slopes (Fig. 5). The Visual strategy seemed to be as successful during the first transfer session as during the NF training sessions. No Strategy was the most successful one during the transfer sessions.

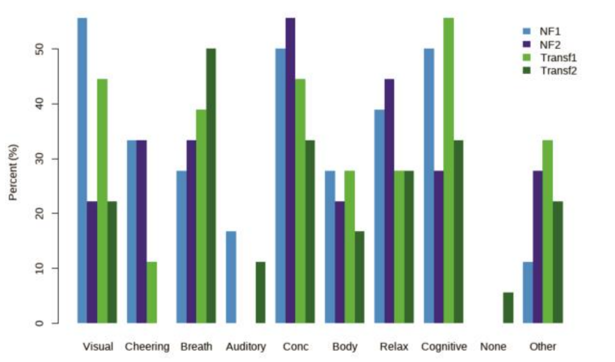

Figure 4: Percentage of participants reporting a specific mental strategy during the first (NF1) and the last NF session (NF2) and during the last two transfer sessions (Transf 1 & 2).

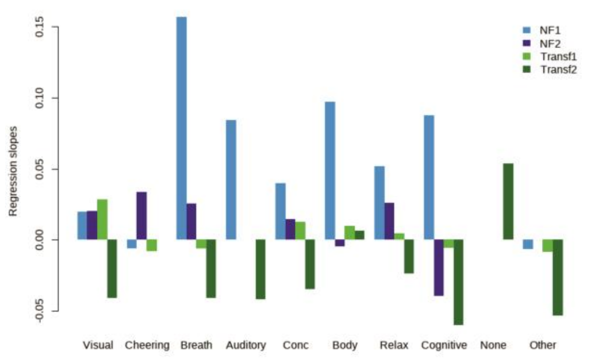

Figure 5: Slopes of linear changes in SMR power across runs within training sessions for the different mental strategies during the first (NF1) and the last NF session (NF2) and during the last two transfer sessions (Transf 1 & 2).

DISCUSSION

Here we focused on the question of mastery of self-regulation of SMR activity during NF training and the generalizability of the NF training results. We were interested in the ability of NF users to increase SMR during transfer trials without any feedback and the used mental strategies during NF training as well as transfer trials.

In line with previous SMR-based NF training studies, participants in the real feedback group were able to linearly increase SMR activity within NF training sessions, while the sham group showed no linear SMR increases [1,7,15,16]. This indicates that the real feedback group was able to increase the target EEG feedback frequency at a given time and that NF learning happened when receiving real-time visual feedback in the real feedback group.

Although the real feedback group showed some form of learning during the NF training sessions, participants were not able to transfer these mental states to a situation without real-time feedback of one's own brain activity, at least after six sessions of NF training. Hence, they did not show a linear increase in SMR activity during the transfer sessions as in the NF sessions. So far, transfer trials were mainly used in SCP-based NF training protocols [8-12]. Most of these prior SCP studies did not report on SCP changes during the transfer trials. Studies reporting changes in SCPs during transfer trials reported heterogenous results [11,12]. Some participants managed to transfer successful self-regulatory processes to situations without feedback, others did not [12]. Kleih-Dahms et al. [12] defined the start of the transfer trials individually depending on the SCP control during NF training. When participants successfully controlled their SCP, transfer trials were included in the NF training. This took between 15 and 17 sessions [12]. In this study, we analyzed group data rather than individual data. Transfer sessions started after the sixth NF training sessions. It may be beneficial to customize the start of transfer sessions based on NF training performance also in SMR-based NF training protocols.

Participants tried multiple different mental strategies during NF training as well as during the transfer sessions. This is in line with prior SMR-based NF training studies that also analyzed the used mental strategies [4-6]. These prior studies also consistently revealed that the strategy "Concentration" is one of the most frequently reported mental strategy during SMR-based NF training [4-6], which might be caused by the instruction of being physically relaxed but mentally focused and concentrated during NF training. "Visual" and "Cognitive" strategies are also often mentioned by participants to increase SMR during NF training [4-6]. But the most frequently mentioned mental strategies are not necessarily the most successful. As in previous studies, breathing strategies are rarely used, but are among the most successful strategies during NF training [4-6]. Surprisingly, these breathing strategies were no longer successful in the transfer trials, although even more participants reported

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using them. The “Visual” strategy seemed to be as successful during the first transfer session as during the NF training sessions. In the transfer sessions, participants mentioned here to visualize the moving bars which they have seen in the previous NF sessions. This strategy successfully led to an increase in SMR power over the runs of the first transfer session, which was performed directly after the last NF training session, but not of the second transfer session, which was performed one week after the first transfer session. Having no specific mental strategy (“None”) turned out to be the most successful one during transfer trials. Previous SMR-based NF training studies also showed that NF users that learned to increase SMR successfully also stopped to use any specific mental strategy [6]. An uncontrolled attempt to use too many mental strategies at once or alternately could overload cognitive resources and could be detrimental to the mental state needed to produce SMR.

CONCLUSION

We could not show that NF users are able to transfer mastery of self-regulation of SMR activity achieved during NF training to other situations without visual feedback. Also, successful mental strategies used during NF training could not be transferred. An individual adjustment of the start of the transfer sessions depending on the NF training success could be useful and should be investigated in future studies.

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