Does Feedback Design Matter? A Neurofeedback Study Comparing Immersive Virtual Reality and Traditional Training Screens in Elderly

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Abstract

Neurofeedback (NF) is a Brain-Computer Interface (BCI) application, in which the brain activity is fed back to the user in real-time enabling voluntary brain control. In this context, the significance of the feedback design is mainly unexplored. Highly immersive feedback scenarios using virtual reality (VR) technique are available. However, their effects on subjective user experience as well as on objective outcome measures remain open. In the present article, we discuss the general pros and cons of using VR as feedback modality in BCI applications. Furthermore, we report on the results of an empirical study, in which the effects of traditional two-dimensional and three-dimensional VR based feedback scenarios on NF training performance and user experience in healthy older individuals and neurologic patients were compared. In conclusion, we suggest indications and contraindications of immersive VR feedback designs in BCI applications. Our results show that findings in healthy individuals are not always transferable to patient populations having an impact on serious game and feedback design.

Keywords: *Aging, Brain-Computer Interface, Feedback design, User Experience;*

1. Introduction

Brain-Computer Interfaces (BCI) enable the control of external devices such as wheelchairs or computers via self-regulation of brain activity [1]. Neurofeedback (NF) is a specific BCI application, in which the user receives real-time feedback of one's own brain activity, in most cases of the electrical brain activity assessed with the electroencephalogram (EEG). Specific components of the EEG are extracted online and fed back to the user for instance via visual or auditory feedback. This enables the user to consciously perceive his or her own electrical brain activity, which is otherwise impossible since there are no somatic receptors to register the electrical brain activity as measured by the EEG. Consequently, the user learns associations between specific mental states and desired brain activation patterns [2–4]. Voluntary modulation of specific EEG parameters generally leads to improvements in behavior and cognition [2, 5, 6].

A critical issue in BCI and NF studies is the fact that a substantial proportion of BCI and NF users fail to gain significant control over their brain signals even after repeated training sessions. About 15–30% of potential BCI or NF users cannot attain control over their own electrical brain activity [6–8]. In the BCI community, this inability to use BCI applications is called "BCI-illiteracy phenomenon" [8]. There are different attempts to explain this phenomenon, but the definite reason why some people cannot control their own brain signals remains largely elusive. Nevertheless, there are some prior studies providing evidence for physiological as well as psychological predictors of successful BCI and NF performance [3, 8–17]. For instance, motivation of the user turned out to play a crucial role [15].

Furthermore, the number of training sessions necessary to obtain any cognitive or behavioral improvements is a critical point, too. The number of training sessions with healthy individuals has ranged from one to thirty-five to obtain successful outcomes [18]. In the clinical context, the number of NF training sessions recommended to reach any clinically relevant improvements is higher. For instance, the number of training sessions necessary to increase attention and decrease impulsivity in patients with attention deficit hyperactivity disorder (ADHD) varies between 17 and 50 sessions [19]. To reduce the number of seizures in epilepsy patients two to five NF training sessions per weak over a period of six to 18 months are recommended [20]. Hence, NF and BCI is relatively time and cost intensive. Such a high number of repeated training sessions can make users bored and tired, which might reduce the compliance of the user [21]. Furthermore, it might decrease the users' ability to focus and concentrate on the task over a longer training period [22], which is also necessary for successful NF/BCI performance [4, 12, 13, 23, 24].

In this context, the feedback design might play a crucial role. Traditional feedback modalities use auditory or visual stimuli or a combination of both. Auditory feedback might be a sound (e.g., the sound of a waterfall, birds singing), a tone or a melody changing its volume or pitch in dependence on the brain activity level [25, 26]. Visual feedback often uses two-dimensional (2D) moving objects such as bars or circles changing their size or color in dependence on the brain activity level [6, 26, 27]. Such relatively monotonous feedback methods might not encourage users to focus on them [28], leading to decreased motivation, interest, concentration, and finally to a lower NF performance and success rate [15]. Hence, an increasing number of recent NF and BCI studies use game-like and/or virtual reality (VR) based feedback designs [21, 26, 28, 28–41]. Kober et al. (2017) summarized BCI and NF studies that used games and VR scenarios as feedback modality in a recent review [42]. In the present study, we focus on the effects of VR based NF training scenarios.

1.1 Possible advantages of VR based NF training scenarios

VR based NF modalities might have beneficial effects on the NF training performance as well as on the NF training outcome due to different reasons. First, an immersive and entertaining VR feedback design might increase the users' motivation, interest and adherence to training [28, 43, 44]. Kober et al. (2016) could show that VR based NF training led to increased motivation and interest in neurologic patients during training compared to a traditional 2D feedback modality. However, the three-dimensional (3D) VR scenario had no beneficial effects on NF training performance [26]. Leeb et al. (2006) also reported that motivation was higher in a VR based feedback paradigm than in a traditional BCI paradigm [45].

Second, the use of an advanced technology such as VR can provide the user with realistic and explanatory feedback about what is going on in the brain during NF training, rather than abstract unintuitive feedback [29]. Some prior BCI and NF training studies already tried to visualize the brain activity on 3D brain models to provide such an explanatory feedback [26, 29–32]. In this context, there is evidence that using 3D virtual bodies as feedback scenario can induce a sense of agency and an illusion of body ownership transfer [46, 47]. Alimardani et al. (2014) investigated the effects of using virtual humanlike robotic hands as visual feedback during a motor imagery based BCI training on the BCI performance. Participants of their study imagined hand movements and when the brain activation patterns during motor imagery were classified successfully the virtual hands moved. Using such a realistic feedback might reduce the mismatch between the participant's life experience and the BCI task, which might interfere with the movement imagination and consequently might impair the motor imagery performance. The authors found that the intensity of the ownership illusion of the virtual hands was positively associated with the BCI motion control [47]. In motor imagery based BCI tasks, the BCI performance might be also improved when using virtual limbs as feedback scenario due to the fact that movement observation affects motor areas in the brain by recruiting the mirror neuron system [48–51]. However, there are also studies that did not find any beneficial effects of using virtual limbs as feedback modality on motor imagery based BCI performance. For instance, Neuper et al. (2009) compared realistic 3D feedback in the form of grasping virtual hands with traditional two-dimensional abstract feedback in the form of an extending bar on a computer screen. They found no differences in the BCI performance between these two feedback modalities [48].

A third reason why VR based NF modalities might have beneficial effects on NF training outcome are immersion and the "sense of being there", otherwise known as presence experience, in VR, which might play an important role, too [52]. Immersion and the presence experience in VR are considered as the propensity of users to respond to virtually generated sensory data as if they were real [53]. There is evidence that highly immersive scenarios foster the transfer of knowledge/skills acquired in the virtual environment to corresponding real world behavior [53]. Such a transfer is also relevant for NF applications. One aim of NF is that after multiple training sessions the user should be able to reproduce the mental state, which is associated with the desired brain activity, without any feedback in real world scenarios. In this context, Gruzelier et al. (2010) could show that using a 3D virtual theatre auditorium as feedback modality during NF training led to an improved real world acting performance in comparison to a 2D feedback condition [40].

1.2 Possible disadvantages of VR based NF training scenarios

Beside positive effects of VR based feedback modalities on NF/BCI performance and outcome, such an advanced technology might be also associated with some disadvantages. Especially, when testing older individuals who are not used to computer technology, one should keep in mind that older individuals are often afraid of making failures when using such an advanced computer technology and that there is some kind of technology gap in the elderly [54, 55]. Using VR based feedback might also overstrain cognitive resources of older users during training, possibly leading to reduced training success and NF outcome. In line with this assumption, Kober et al. (2016) reported that older stroke patients showed higher values in incompetence fear and lower values in mastery confidence when using a 3D VR feedback scenario compared to a traditional 2D NF screen [26]. Mercier-Ganady et al. (2014) also reported that a VR feedback scenario was subjectively rated as less simple and less clear compared to traditional simpler feedback modalities [29].

Using VR as feedback modality is often related to the use of technical equipment such as stereoscopic glasses or head-mounted displays. Such technical equipment might on the one hand disturb the EEG signal by producing electrical artifacts in the signal. On the other hand, wearing such equipment during NF or BCI training might also disturb the user and might lead to some discomfort. Consequently, the user might get annoyed. Furthermore, wearing such technical objects on the head might increase the production of muscle artifacts leading to a disturbed EEG signal as well, which consequently has a negative impact on the NF or BCI performance.

The use of VR technology might also cause physical side-effects including ocular problems, disorientation, and nausea, often referred to as simulator sickness or cyber sickness. Such cyber sickness symptoms can potentially confound data and compromise the potential value of VR based feedback designs [56].

Another critical point in this context is the lack of empirical evidence of positive effects of VR or game based feedback modalities [42]. Although it is assumed that VR based feedback should have positive effects on motivation, interest, compliance, or training outcome, up to date only a few studies have actually investigated these effects. For instance, the user experience is mainly assessed by subjective reports of the users if assessed at all. The use of questionnaires, rating scales or structured interviews is rare and thus comprehensive objective evaluation of VR based feedback effects is largely missing [42].

1.3 Aim of the present empirical study

Based on the above mentioned lack of empirical evidence concerning the effectiveness of VR based NF modalities, we performed an empirical study investigating the effects of 3D VR based feedback and traditional 2D feedback modalities on the NF training performance as well as on the subjective user experience including psychological constructs such as training motivation, mood, interest, challenge, anxiety, and mastery confidence. Hence, in this first study we focused on the effects of dimensionality (2D vs. 3D). We used a 3D virtual human body, whose organs such as the brain, heart or vascular system changed in appearance depending on the feedback training results, and traditional 2D moving bars as feedback modalities. The virtual body provided an anatomically realistic visualization of the NF process. The direct illustration of NF training-related electrophysiological changes in the brain using the virtual body may lead to a better understanding of what is happening in the brain during NF training and might enhance the training outcome [26, 29]. Evaluating the effects of 2D and 3D feedback modalities on objective performance measures and subjective user experience will provide new insights in the impact of serious game and feedback design in different user populations (e.g., healthy individuals vs. patients).

2. Empirical study

In a NF training study, we investigated the effects of traditional 2D feedback and 3D VR based feedback on the subjective user experience as well as the NF training performance in healthy older individuals as well as in two stroke patients.

2.1 Methods

2.1.1 Participants

Twenty-four healthy older individuals took part in this study. Participants were randomly assigned to one of two groups: One group received traditional 2D feedback (moving bars) and formed the 2D group (*N*=12, 9 females, Mean age = 62.50 yrs., *SE* = 1.60 yrs.), and the second group received 3D VR based feedback (virtual body) and formed the 3D group (*N*=12, 7 females, Mean age = 62.75 yrs., *SE* = 1.98 yrs.). Participants were not informed about the grouping design, nor did they know that there were different feedback conditions. All volunteers gave written informed consent and were paid for their participation (100€).

Furthermore, we recruited two stroke patients who performed the 3D VR based NF training. Patient A was a 73 year old man. A few years before the NF training, he had suffered an ischemia in the left middle cerebral artery. The patient did not show motor deficits or severe cognitive deficits. Patient B was a 52 year old woman, who suffered a stroke about two years before the NF training, resulting in lesions in the brainstem. She showed slight attentional and memory deficits.

Exclusion criteria were: drug treatment that interferes with the vigilance state, visual hemi-neglect, dementia (MMSE < 24, [57]), psychiatric disorders such as depression or anxiety, concomitant neurological disorders, e.g. Parkinson disease or visual-reflex epilepsy, aphasia, insufficient motivation and cooperation. All participants had normal or corrected-to-normal vision and hearing. The ethics committee of the University of Graz, Austria approved all aspects of the present study in accordance to the Declaration of Helsinki (GZ. 39/11/63 ex 2013/14, GZ. 39/22/63 ex 2012/13, GZ. 39/22/63 ex 2011/12).

2.1.2 Neurofeedback Training

For the NF training the EEG signal was recorded using a 10-channel amplifier (NeXus-10 MKII, Mind Media BV) with a sampling frequency of 256 Hz, the ground was located at the right mastoid, the reference was placed at the left mastoid. All participants performed ten NF training sessions on different days three to five times per week, only patient A performed six NF training sessions. One NF training session lasted approximately 45 minutes and consisted of seven runs with a duration of 3 minutes each. The first run was a baseline run in which no real-time feedback was provided. In the consecutive six feedback runs, participants got visual feedback about their EEG activity (either 2D or 3D). An Upper Alpha (UA, 2 Hz above the individual alpha frequency [58]) feedback protocol was used, in which participants should learn to voluntarily increase their UA activity. The individual alpha frequency was determined based on a resting measurement with open eyes before the start or the NF training. Pz was used as feedback electrode. Note that patient B was the only one who trained to up-regulate the 12-15 Hz rhythm over electrode position Cz instead of UA.

The traditional 2D visual feedback screen showed three vertically moving bars on a conventional computer screen [6, 59]. A larger bar in the middle of the screen changed its size depending on the EEG amplitude of the trained EEG frequency (Figure 1). The participants' task was to move this bar up. Two further moving bars were placed on the left and on the right side of the screen, which should be kept as low as possible. These two bars were control bars that increased when ocular (Theta frequency in a range of 4-7 Hz) or movement artifacts (Beta frequency in a range of 21-35 Hz) were too strong. A three minutes baseline run at the beginning of each training session, in which participants were instructed to relax, was used to calculate individually defined thresholds (mean UA power for bar in the middle of the screen; Mean +1 *SD* of Theta and Beta power for control bars, respectively) for the subsequent feedback runs. When participants were successful in voluntarily modulating the trained EEG frequency in the desired direction while keeping artifacts low, they got reward points indicated with a reward counter placed at the bottom of the screen and the moving bars changed their color from red to green. Participants gained a reward point whenever the bar in the middle of the screen exceeded the individually defined threshold and fall below the thresholds of the control bars for >250 ms.

To provide 3D visual feedback, a commercial BenQ 3D Vision stereoscopic 24" display was used. For the stereoscopic effect, a lightweight pair of stereoscopic glasses was used. On the 3D display, participants saw a virtual 3D semi-transparent stereoscopic render of a human body, which was developed with Unity3D and whose organs (brain, heart and vascular system) changed in appearance depending on the NF training results. Additionally, a lightbulb was included in the scene to reinforce the feedback effect. When participants successfully modulated the trained EEG frequencies while keeping artifacts low, the virtual brain was tinted green and the lightbulb got brighter. Otherwise, the brain became red and the lightbulb darker. On the left lower corner of the feedback screen, small moving bars could be additionally seen depicting UA, Theta and Beta power. During the training, a reward counter acting as a score (shown as a pink number in the upper left corner of the screen) increased when the goals of the training were achieved. Threshold settings, feedback frequencies, and reward counter calculations were the same as for the 2D feedback scenario. Figure 1 illustrates example pictures of the 3D VR visual feedback during the baseline run and the feedback runs.

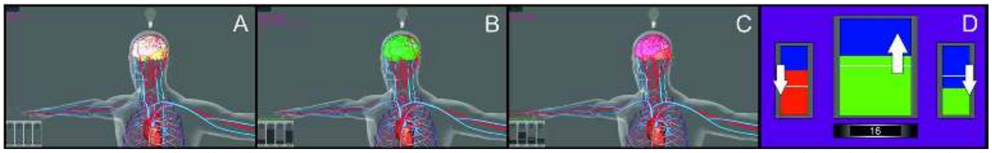

Figure 1. Visual feedback screens. Virtual 3D semi-transparent stereoscopic render of a human body during the baseline run (A), and during the feedback runs while receiving positive (B) or negative (C) feedback. Traditional 2D visual feedback screen showing vertically moving bars (D).

EEG data analysis was performed offline using the Brain Vision Analyzer software (version 2.01, Brain Products GmbH, Munich, Germany). Artefacts (e.g. eye blinks/movements, muscle activity) were rejected by means of a semi-automatic artefact rejection (criteria for rejection: > 50.00 µV voltage step per sampling point, absolute voltage value > ±100.00 µV). To analyze the feedback training data, absolute power values of the trained EEG frequencies were extracted using the Brain Vision Analyzer's built-in method of complex demodulation and averaged separately for each 3-minute feedback run of each session.

2.1.3 Questionnaires and Rating Scales to Assess User Experience

Mood and motivation were assessed during the first and last NF training session using a visual analogue scale (VAS) ranging from 0-100 and a standardized motivation questionnaire, the Questionnaire on Current Motivation (Fragebogen zur Erfassung Aktueller Motivation, FAM, [60]). The FAM uses 18 items to measure four motivational factors in either field or laboratory learning and achievement situations: Incompetence Fear (anxiety), Mastery Confidence (probability of success), Interest, and Challenge. The Simulator Sickness Questionnaire (SSQ) was used to determine whether participants using the VR NF paradigm experienced cyber sickness symptoms [61]. The short SSQ was completed before and after each VR based NF training session.

2.1.4 Statistical Analysis

In order to analyze the NF training performance, we determined the time course of the trained EEG frequencies averaged over the NF training sessions across the six feedback runs using linear regression analysis. In addition, a one-sample *t*-test against 0 was calculated to verify the consistency of the learning effects.

To analyze whether there is a significant change in motivation, mood and the FAM sub-scores as assessed with questionnaires and rating scales in the healthy group, univariate repeated-measures analyses of variance (ANOVA) with the between subjects factor group (2D vs. 3D group) and the within-subjects factor time (first vs. last NF training session) were calculated.

Single case analysis methods [62, 63] were used to compare the results of the single patients that performed the 3D NF task with the results of the healthy 3D control group.

2.2 Results

2.2.1 Neurofeedback Performance

While the 3D group was able to linearly increase their UA power during NF training, the 2D group was not. One sample *t*-tests revealed that the individual regression slopes for UA power of the 3D group differed by trend from zero ($t(11) = -1.41$, $p < 0.10$). The 2D group showed a positive regression slope, however, the regression model did not reveal significant effects. Both patients showed a linear increase in the trained EEG frequency across the training runs. Single case analysis revealed that the regression slopes of the single patients did not differ from the regression slope of the 3D group. Hence, the single stroke patients were as successful when trying to upregulate their UA power during NF training as the healthy 3D group. The average slope of UA power over the feedback runs and the results of the regression analyses are shown in Figure 2, separately for the 2D and 3D group and the stroke patients.

Theta power (Figure 2), which was used as control frequency during NF training indicating eye artifacts, linearly decreased in the healthy control groups.

Beta power (Figure 2), which was used as second control frequency and which was related to muscle artifacts, also decreased during the NF training, as indicated by negative regression slopes, except for patient B.

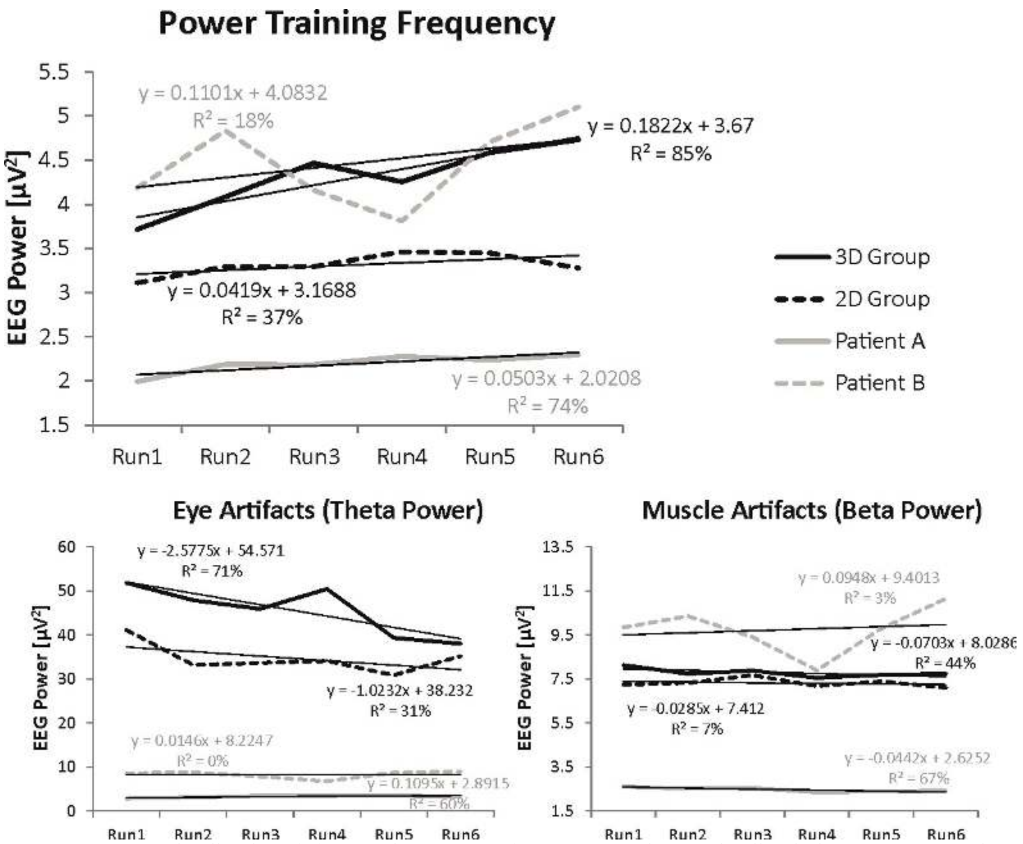

Figure 2. Neurofeedback training performance. Time course of EEG feedback frequency over the six NF training runs, averaged over all NF training sessions, presented separately for the healthy 2D and 3D groups as well as patient A and B who performed the 3D VR NF training (upper panel). The lower two panels show the time course of the two control frequencies, respectively. The results of the regression analysis and the regression slopes are added as well.

2.2.2 Questionnaire and Rating Scale Data

The results for the 2x2 ANOVAs with the between subject factor group and the within-subject factor time are depicted in Table 1 separately for each questionnaire and rating scale item. No significant effects were observed for the VAS rating Motivation. However, descriptively the 3D group showed higher values in motivation during the first NF training session than the 2D group (Figure 3). Mood increased by trend ($p < 0.10$) in both groups from the first to the last NF training session (Table 1, Figure 3). For the FAM subscale Confidence, the ANOVA revealed a significant interaction effect group*time (Table 1). Posttests revealed that in the 3D group confidence increased from the first to the last NF training session while in the 2D group confidence did not change significantly (Figure 3). Fear was overall higher in the 2D than in the 3D group and decreased from the first to the last NF training session by trend in both groups (Table 1, Figure 3). Interest was by trend higher in the 3D than in the 2D group (Table 1, Figure 3). No significant effects were found for the FAM subscale Challenge. There were no group differences in the SSQ assessing simulator sickness. A significant main effect of time (Table 1) indicated that sickness symptoms were overall lower during the last NF training session ($M = 5.79$; $SE = 1.29$) than during the first ($M = 9.63$; $SE = 2.12$).

Single case analysis comparing the results of the two single stroke patients with the 3D control group revealed that Confidence was lower in patients than in healthy controls, although the confidence of patient B increased from the first to the last NF training sessions. In contrast, patient B showed an increased Fear during the last NF training session compared to the 3D control group. Interest was lower in patient A than in the 3D group but only during the first session. Overall, patient B showed a reduced Mood (Figure 3). Motivation and Challenge did not differ statistically between the single patients and the healthy 3D group.

Table 1. Summary of the 2x2 ANOVAs (*F*-values) for the questionnaire and rating scale data.

	VAS Motivation	***VAS Mood***	***FAM Confidence***	***FAM Fear***	***FAM Interest***	***FAM Challenge***	***SSQ***
Group	0.81	1.58	0.32	4.80*	3.95^{+}	0.02	0.22
Time	0.16	3.08^{+}	2.16	3.19^{+}	0.14	0.86	7.95*
Group*Time	1.19	0.30	4.54*	0.24	0.01	1.69	0.03

*$p < 0.05$; $^{+}p < 0.10$

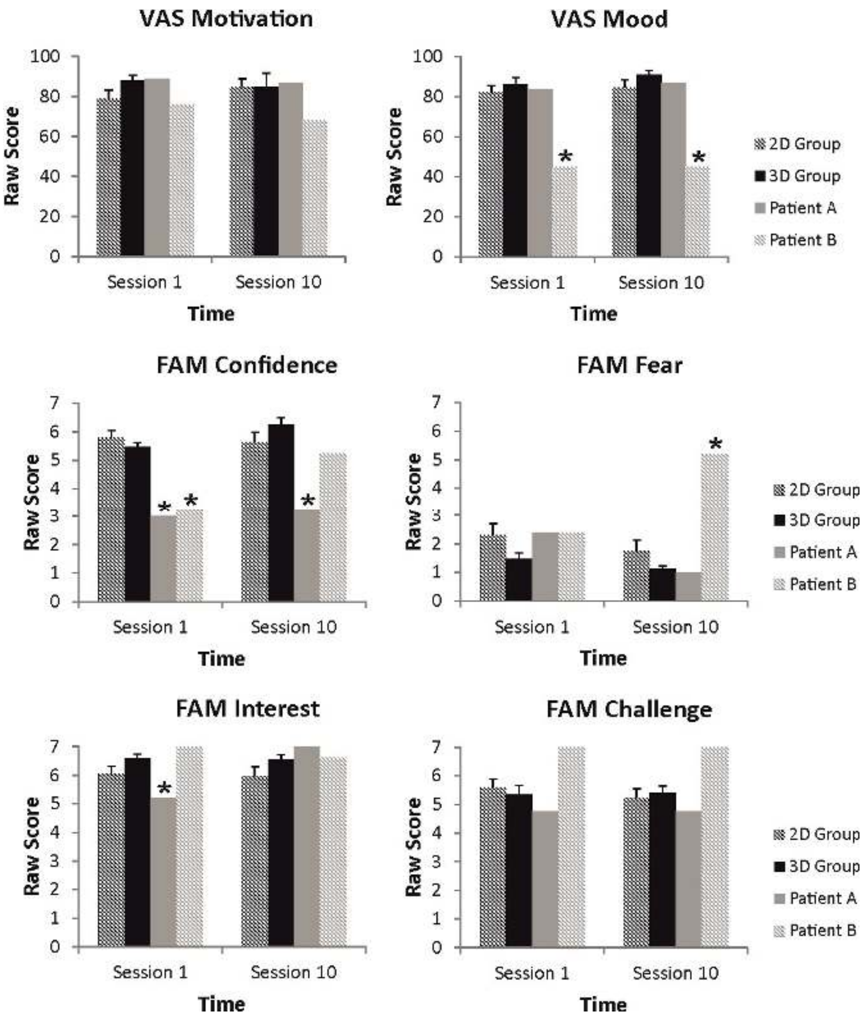

Figure 3. Results (Means and *SE*) of questionnaire and rating scale data, presented separately for the 2D and 3D group and patient A and B who performed the 3D NF scenario. Significant results of the single case analysis (comparison of results of single patients with 3D group) are marked with asterisks (*$p < 0.05$).

3. Discussion and Conclusion

The aim of the present study was to evaluate the effects of a 3D VR based feedback scenario on user experience during NF training as well as on the NF training outcome.

3.1 Effects of 2D and 3D VR based feedback scenarios on NF training performance

The 3D group showed an improved NF training performance compared to the 2D group. While both groups showed a linear increase in UA power during NF training, the regression model was only significant for the 3D group. Hence, the 3D VR feedback led to a superior NF performance compared to the traditional 2D moving bars in healthy controls. This is in contrast to a prior single case study investigating stroke patients, in which the same 2D and 3D feedback modalities were used. This prior study found no differences in the NF training performance between the 2D and 3D condition [26]. However, results of studies investigating neurologic patients and studies investigating healthy subjects are not directly comparable. Probably, neurologic patients need more time or a larger amount of training sessions to get used to the VR feedback than healthy individuals and to reveal any beneficial effects of VR based NF training on the training outcome [26, 29]. Prior NF training studies that investigated the effects of VR feedback scenarios on NF performance in healthy subjects reported heterogeneous results [21, 28, 29, 40, 41, 48]. However, based on the present findings we conclude that the 3D VR feedback had beneficial effects on the NF training performance in healthy older individuals.

Both patients who received the 3D VR feedback were able to linearly increase the trained EEG frequency bands during NF training.

The two control frequencies, which should be reduced during NF training to prevent eye and muscle artifacts, showed a linear decrease during training, especially in healthy controls. This indicates that healthy controls were able to keep these artifact frequencies low during NF training, independent of the feedback modality.

3.2 Effects of 2D and 3D VR based feedback scenarios on user experience

In line with our assumption that a VR based NF training scenario should increase interest and motivation, consequently leading to an improved NF training performance, the 3D group showed by trend higher levels of interest than the 2D group. Although not statistically significant, motivation was also numerically higher in the 3D than in the 2D group. This is in line with our prior study in stroke patients [26] and indicates that new and innovative VR applications have the potential to attract and motivate users more than classical 2D feedback screens [28, 44].

In contrast to our findings in stroke patients in a previous study [26], the healthy 3D group showed lower levels of incompetence fear than the healthy 2D group and mastery confidence increased from the first to the last NF training session in the 3D group. Hence, again the results in healthy individuals are in contrast to the results in neurologic patients. Confirming that, the two single stroke patients presented in the present study show a lower confidence and a higher fear than the healthy 3D group. Kober et al. (2016) argued that incompetence fear was higher and mastery confidence was lower in stroke patients receiving VR feedback than in patients receiving 2D feedback because the 3D VR feedback might have been more complex and less simple and clear than the traditional 2D feedback [26, 29]. This might have strengthened the negative affect of the generally refusing attitude towards computer technology in elderly [55]. However, we cannot confirm this in healthy older individuals. The 3D VR feedback design seems to foster positive affects towards this technology, going along with positive emotions, motivation, and interest.

Patient B showed an overall decreased mood, which might not have been related to the VR based NF training per se. General mood disturbance in this patient might also explain why fear increased in this patient from the first to the last NF training session.

The used 3D VR feedback modality did not lead to any cyber sickness symptoms. Furthermore, the used VR technology (stereoscopic glasses) did not disturb the EEG signal. The EEG data quality was comparable between the 2D and 3D feedback modality.

3.3 3D feedback scenario

In the present investigation, we used a 3D virtual human body, whose brain changed its color depending on the users' brain activation state. Furthermore, small moving bars on the left lower corner of the 3D feedback screen provided the same information than the moving bars in the 2D traditional feedback condition (Figure 1). Hence, the 3D brain was an additional feedback information compared to the 2D feedback scenario. The stereoscopic view of the 3D brain did not add any essential feedback information but should provide a stronger sense of presence in the 3D than in the 2D condition. Changing the color of the whole brain when reaching the desired brain state, as implemented in the present investigation, might not be detailed enough to provide instructive feedback about what is exactly going on in the brain during NF training. Instead, it might be useful to give feedback about the precise topographical distribution of changes in the brain during NF [29]. A more fine graded, realistic, and explanatory feedback than the feedback used in the present study might also support the NF performance, sense of agency and the illusion of body ownership transfer [46, 47].

3.4 Conclusion and future directions

In conclusion, our results indicate that the effects of a more advanced VR based feedback modality are different between healthy individuals and neurologic patients. While we found mainly positive effects of VR feedback in healthy older people, the 3D VR feedback showed positive but also negative effects in neurologic patients, e.g., patients showed lower levels of confidence and higher fear. Hence, findings in healthy individuals are not always transferable to patient populations, which should be considered when designing serious games and feedback modalities in the future. Furthermore, the usefulness of 3D VR feedback scenarios in the context of neurological rehabilitation is questionable. While our findings in healthy older individuals demonstrated throughout positive effects, VR based NF training also lead to negative user experience in stroke patients. However, these effects were observed in only two single-stroke patients. A larger sample of stroke patients is needed to draw any meaningful conclusions concerning the effects of VR based feedback modalities in neurologic patients.

In this first study, we kept the 3D VR feedback scenario rather simple. For a more profound evaluation of the potential value of VR technology in neurofeedback applications, future studies investigating the effects of more complex, realistic and immersive VR feedback scenarios are necessary.

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