

Behavioural and Neural Predictors of Learning Success in MVPA-Based Real-Time fMRI Neurofeedback: A Proof-of-Concept Study

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Introduction

Real-time fMRI neurofeedback (rt-fMRI-NFB) has emerged as a promising technique that enables voluntary modulation of brain activity and has been applied to modify behaviour and reduce symptom severity in psychiatric disorders (Pindi *et al.*, 2022). However, there is substantial inter-individual variability in neurofeedback learning success, and a considerable proportion of participants fail to achieve reliable self-regulation of target brain activity (Alkoby *et al.*, 2018).

Identifying factors that contribute to this variability is critical for optimizing neurofeedback interventions and developing more individualized training approaches (Weber, Ethofer and Ehlis, 2020). Previous research has investigated a range of potential predictors, including neural and psychological factors, but findings remain inconsistent. For example, while baseline activity in the target region has been proposed as a promising neural predictor (Weber, Ethofer and Ehlis, 2020), other studies found no reliable association between pre-training ROI activity and neurofeedback success (Hugg *et al.*, 2020). Similarly, a recent systematic review highlighted subject-specific factors, such as attention and motivation, as potential predictors of neurofeedback learning, although empirical evidence remains limited (Kadosh and Staunton, 2019).

Importantly, existing predictor research has focused primarily on univariate and connectivity-based neurofeedback approaches, with little evidence available for multivariate pattern-based neurofeedback (MVPA-NFB). In this proof-of-concept study, we investigated whether behavioural and neural measures could predict individual differences in learning success during MVPA-based rt-fMRI neurofeedback targeting auditory verbal imagery (AVI) -related brain activity.

Methods

Twenty healthy participants completed four visits, including a virtual reality training session, an MRI training session, and two rt-fMRI-NFB sessions. During training, participants learned cognitive strategies to modulate brain states away from the auditory verbal imagery (AVI) network. For the subvocalization (SVA) strategy, participants were trained to modulate subvocal speech using Neutral and Happy prosody conditions. During each rt-fMRI-NFB session, participants received real-time feedback derived from a support vector machine (SVM) classifier trained to discriminate AVI from non-AVI brain states. Feedback scores reflected the current brain state's distance from the classifier hyperplane.

To investigate factors associated with neurofeedback learning, analyses focused on the SVA condition. Learning success was quantified as the slope of individual neurofeedback learning curves across training runs. Potential predictors included behavioural and neural measures. Behavioural predictors comprised (i) attentional performance, assessed during the first visit using the Test of Attentional Performance (TAP) Alertness task, and (ii) confidence, assessed via self-reported ratings of strategy usefulness and ease of implementation averaged across post-session questionnaires. Neural predictors, derived from the MRI training session, included (i) univariate activation differences between Neutral and Happy SVA conditions obtained from general linear model (GLM) analyses and (ii) representational distances between Neutral and Happy SVA conditions derived from representational similarity analysis (RSA). Neural predictors were examined across four predefined regions of interest (ROIs): STG, IFG, SMA and Amygdala. Associations between learning success and predictor variables were evaluated using correlation analyses. P-values from ROI-wise correlation analyses were corrected for multiple comparisons using the Benjamini–Hochberg false discovery rate (FDR) procedure.

Results

Confidence showed the strongest association with neurofeedback learning success ($r = 0.582$, $p < 0.01$). Attentional performance was positively, but not significantly, associated with learning success ($r = 0.421$, $p = 0.06$). Among neural predictors, greater GLM-derived activation differences between Happy and Neutral SVA conditions in the amygdala were associated with higher learning success ($r = 0.467$, $p_{unc} = 0.03$, $pFDR = 0.15$), although this association did not survive FDR correction. No significant associations were observed for GLM-derived activation differences in the STG, IFG, or SMA, nor for RSA-derived representational distances in any ROI.

Conclusions

Overall, these findings provide preliminary evidence that behavioural factors may contribute to inter-individual variability in neurofeedback learning success in MVPA-based rt-fMRI-NFB. In particular, confidence showed the strongest association with learning success, while attention was positively but not significantly related to learning. This suggests that subjective appraisal of strategy effectiveness during training may play a relevant role in successful neurofeedback performance, potentially reflecting engagement with or perceived controllability of the task.

In contrast, neural predictors derived from MRI training showed more limited associations with learning success. A positive association was observed between univariate activation differences between Happy and Neutral SVA conditions in the amygdala and learning success; however, this effect did not survive correction for multiple comparisons. No associations were observed for activation differences in the other ROIs or for representational similarity-based measures.

Taken together, these findings highlight behavioural measures, particularly confidence, as potentially relevant candidate predictors of neurofeedback learning. However, future work is needed to validate these findings in larger samples and identify reliable predictors of inter-individual variability in MVPA-based neurofeedback learning.

References

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