Neurofeedback-based Brain–computer Interface for Pain Management: A Research Perspective

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Persistent pain is a complex and highly individualised experience, existing on a dynamic continuum that does not affect everyone equally (García-Rodríguez et al., 2023). Persistent pain remains one of the most prevalent and disabling conditions worldwide, impacting 20–30% of the population and affecting more than half of older adults (El-Tallawy et al., 2021). In Aotearoa New Zealand, one in five people live with chronic pain, placing a significant burden on individuals, their whānau, and the broader healthcare system (Abbott et al., 2017). While conceptually compelling, the pain experience associated with persistent pain conditions does not always have a relationship to the underlying aetiopathology. Research has shown that persistent pain is associated with widespread changes in brain activity and functional connectivity in regions involved in pain perception and experience (De Ridder et al., 2021).

The experience of pain is a complex and dynamic process that integrates multiple factors, including sensory perception, emotional and cognitive components, and the pain-inhibitory mechanisms of the brain (Vanneste & De Ridder, 2021). These dynamic interactions between pain-related brain regions and networks are driven by brain oscillations (waves) (Ploner et al., 2017). Notably, electroencephalographic (EEG) studies have identified distinct changes in brain oscillations across acute, chronic, and experimentally induced musculoskeletal pain conditions (Mathew, Perez, et al., 2022). For example, an inverse relationship has been observed between the strength of alpha brain oscillations (the dominant waves that are active during relaxed wakefulness) in the somatosensory cortex and pain sensitivity (Babiloni et al., 2006; Tu, Tan, et al., 2016; Tu, Zhang, et al., 2016). Similarly, reviews highlight alterations in various brain oscillations across various chronic pain conditions (Dos Santos Pinheiro et al., 2016; Mathew, Perez, et al., 2022). If this is the case, modulating these oscillations in the appropriate pain-mediating brain regions should lead to corresponding changes in pain perception and experience. However, the bigger question is: can we modulate these brain wave alterations to influence pain experience?

The field of non-invasive neuromodulation and brain–computer interfaces for pain management is rapidly advancing, offering promising avenues for intervention. Several non-invasive neuromodulation techniques, including neurofeedback (NF), repetitive transcranial magnetic stimulation, and transcranial electrical stimulation, have been explored for pain modulation (Hesam-Shariati et al., 2021; Knotkova et al., 2021). Among these, EEG-based neurofeedback (EEG-NF) stands out as a non-invasive, endogenous brain–computer interface technique with demonstrated efficacy in chronic pain management (Hesam-Shariati et al., 2021; Patel et al., 2020; Roy et al., 2020). EEG-NF operates in a closed-loop system, enabling individuals to learn self-regulation of brain activity through real-time feedback (e.g., visual, auditory, or combined visual and auditory). This approach allows researchers to investigate how brain regulation influences behaviour and pain perception using validated outcome measures (e.g., the Brief Pain Inventory, Numerical Pain Rating Scale, Pain Unpleasantness). The application of EEG-NF has been explored in both animal models and humans, and interest in this field of research has accelerated over the last few decades. The principal goal of EEG-NF is to modulate specific brain oscillations linked to a disease or behavioural state (Strehl, 2014). Each EEG-NF protocol can be designed to train (increase or decrease) a specific brain oscillation through the selected EEG electrode (surface NF) or can be localised to a specific region of the brain (Marzbani et al., 2016) using advanced neuroimaging technologies (Adhia et al., 2023; Mathew, Adhia, et al., 2022). Figure 1 illustrates the EEG-NF setup and feedback loop.

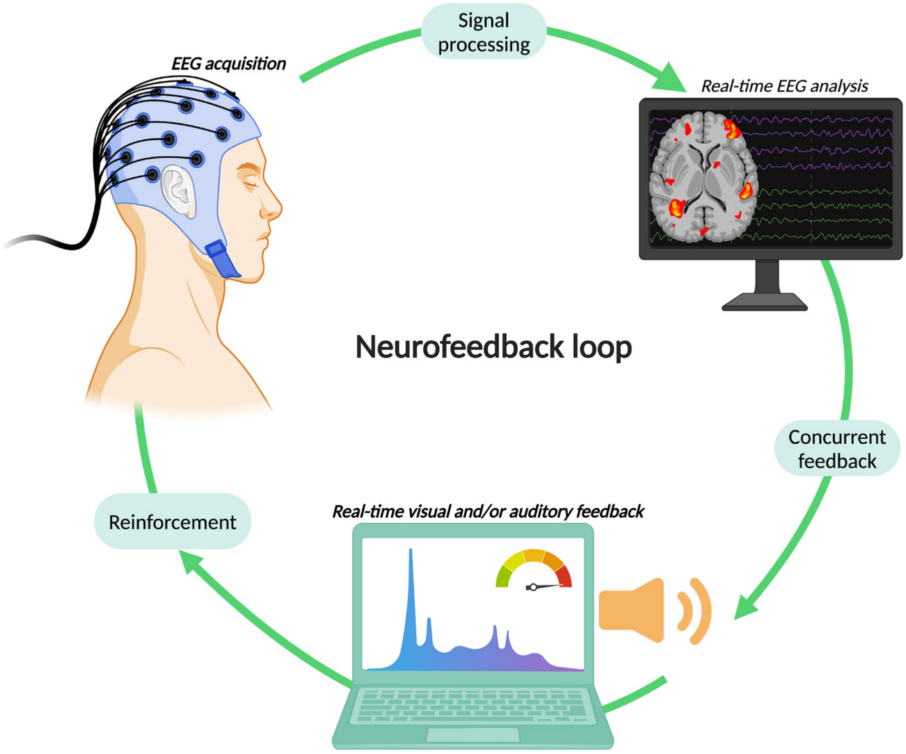
EEG-NF shows promise as a tool for managing various conditions by regulating brain signals through feedback-based learning. Unlike other neuromodulation techniques, EEG-NF necessitates active engagement from the participant to achieve optimal results, and each individual will respond uniquely to the training, which facilitates endogenous neuromodulation. As a result, the time required for successful regulation of brain activity can vary among people. For example, during a 30-minute EEG-NF session, one participant may successfully train their brain waves for 10 min, while another may achieve 20 min of successful training (Mathew et al., 2025). Therefore, it is crucial to account for the duration of successful training for individuals when studying the effects of EEG-NF. Moreover, conventional pre-post group analyses may fail to capture this individual variability, increasing the risk of Type I and Type II errors and potentially masking the true effects of training. This emphasises the need to account for the duration of successful training as a key variable in future clinical trials evaluating the effectiveness of EEG-NF, particularly for chronic pain.

EEG-NF training is based on well-established learning principles, and operant conditioning is a key component. Operant conditioning is a learning process in which behaviour is shaped by its consequences – desired actions are reinforced, increasing the likelihood of their repetition. In EEG-NF, individuals modify their neural responses based on the feedback received, a process known as reinforcement learning. By repeatedly reinforcing specific neural patterns, this training enhances the potential for sustained changes in brain function (Skinner, 1971; Staddon & Cerutti, 2003). A successful change according to the task is

Figure 1

EEG-NF Set-up and Feedback Loop

During EEG-NF, real-time activity and/or connectivity metrics of the targeted brain region(s) are recorded using EEG electrodes placed on the scalp. The signals are processed and analysed in real time to determine whether they meet the training threshold. If the criterion is met – such as uptraining a specific frequency in a designated region – the computer provides feedback as positive reinforcement. This process facilitates the feedback loop, allowing the participant to receive reinforcement each time they achieve the threshold. Created in BioRender. Mathew, J. (2025) https://BioRender.com/m56v825



positively reinforced with feedback (e.g., auditory, visual), while failure to change is not rewarded with any form of feedback, enabling individuals to self-regulate real-time brain activity (Koralek et al., 2012; Strehl, 2014). Despite ongoing debate regarding methodological implementation, operant conditioning remains a fundamental mechanism underlying EEG-NF learning.

Another supporting theory, the Dual-Process Theory, suggests that learning involves both efferent (outgoing) and afferent (incoming) processes. Individuals use cognitive strategies and interoceptive awareness to actively regulate their brain activity (Dunn et al., 1986; Lacroix, 1986; Muñoz-Moldes & Cleeremans, 2020). The CRED-nf (Consensus on the reporting and experimental design of clinical and cognitive-behavioural neurofeedback studies) checklist further supports the integration of cognitive strategies to optimise NF training outcomes. Moreover, the CRED-nf can be a valuable guide for clinicians and for designing robust clinical trials to explore the effects of EEG-NF (Ros et al., 2020).

While extensive research has established the potential of NF for chronic pain management, its clinical translation and implementation remain critical, particularly in Aotearoa New Zealand. The time has come to bridge the gap between research and practice by integrating NF into clinical settings. I strongly believe in the potential of NF as a transformative approach for pain management, and I am hopeful that its widespread adoption will soon become a reality.

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