



# The Impact of Context on EEG Motor Imagery Neurofeedback and Related Motor Domains

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## Abstract

Neurofeedback (NF) is a versatile non-invasive neuromodulation technique. In combination with motor imagery (MI), NF has considerable potential for enhancing motor performance or supplementing motor rehabilitation. However, not all users achieve reliable NF control. While research has focused on various brain signal properties and the optimisation of signal processing to solve this issue, the impact of context, i.e. the conditions in which NF motor tasks occur, is comparatively unknown. We review current research on the impact of context on MI NF and related motor domains. We identify long-term factors that act at the level of the individual or of the intervention, and short-term factors, with levels before/after and during a session. The reviewed literature indicates that context plays a significant role. We propose considering context factors as well as within-level and across-level interactions when studying MI NF.

## Introduction

Learning new motor skills, improving existing motor skills and re-learning weakened or temporarily lost motor skills requires repeated practice. This practice can have many facets, spanning the whole spectrum from predominantly physical processes to purely mental processes. Some of the most prominent variants include (attempted) motor execution (ME), observation, mirror therapy and motor imagery (MI). The effectiveness of each of these variants in sports performance and rehabilitation is largely uncontroversial. It has been critically noted, however, that variants that fall into the mental end of the spectrum miss feedback on performance,

a keystone for directed learning and adaptive cortical reorganisation [1]. A promising solution to this problem is the use of brain-computer-interface (BCI) technology to provide neurofeedback (NF). NF, a closed-loop system, involves measuring an individual's brain activity, analysing the data in real-time and feeding it back to the same individual in an intuitive format. Table 1 provides short explanations of terms and concepts central to MI NF. Like sensory feedback, NF can guide subsequent mental and physical processes. The systematic evaluation of any behavioural gains induced through MI NF practice is generally impeded by the simplicity of applied movements [2–4]. This is because these movements must be suitable for the limited movement capabilities of the clinical target population of paretic stroke patients and must also be appropriate for informative NF. In studies with healthy individuals typically overlearned movements [2–4] can be expected to lead to only small or even not measurable behavioural gains through practice. However, several clinical studies did show behavioural improvements following MI NF practice for these movements (for a review, see [5]). More complex movements may increase the level of difficulty, but may not be transferable to rehabilitation setups, or lack everyday relevance.

Despite numerous technical advances at different points in the NF loop (e.g. online artefact correction, advanced spatial filters, multi-variate classification), which without doubt improve the online signal-to-noise ratio, huge intra- and inter-subject variabilities remain. Understanding the cause(s)

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**Table 1** Key terms for motor imagery neurofeedback

## Key terms

*Motor Imagery*

Motor imagery (MI) is defined as mental representation of a particular motor act without observable motor output. Many different forms of MI exist, such as implicit MI and explicit MI. In explicit MI, individuals are asked to imagine a specific movement or action. In implicit MI, individuals are not instructed to imagine a movement but they receive tasks that require the use of MI. A further distinction is made based on the nature of the mental representation. For kinaesthetic MI, individuals are asked to imagine the feeling of a particular motor act, while visual MI usually targets eliciting a ‘mental video’. MI can be performed from the first- and third-person perspectives. MI NF focuses on explicit, kinaesthetic MI from the first-person perspective, as this combination is characterised by a greater enrolment of the sensorimotor network and holds thus greater potential for motor rehabilitation

*Neuromodulator/neuromodulation*

Neuromodulators alter brain activity. Mostly used when an external source is the cause of the modulation, such as brain stimulation, neurofeedback or pharmacological interventions

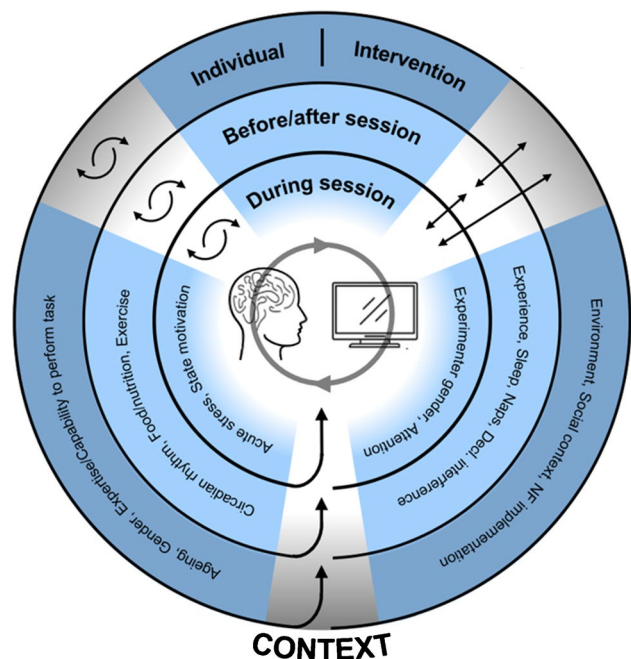
*Neurofeedback*

Neurofeedback (NF) and brain-computer-interface (BCI) enable both a direct connection between the brain and an external device. Moreover, both consist of three modules: data acquisition and data processing, the interface and the user. Despite these similarities and the fact that NF and BCI are often used interchangeably, they depict slightly different concepts. In line with the original definitions dating back several decades, NF is to be user-centred, while BCI is application-centred. Consequently, a system with the aim of changing abnormal brain activation patterns is classed as NF, whereby a system with the aim of steering a device (e.g. a cursor or a wheelchair) is classed as BCI

*SMR*

Sensorimotor rhythm (SMR) refers to activity in the mu (8–12 Hz) and beta (13–30 Hz) frequency range stemming from sensorimotor areas. During cognitive-motor tasks and movement execution SMR activity typically decreases before and during the act, known as event-related desynchronisation (ERD), and increases afterward, known as event-related synchronisation (ERS). Most MI NFs are based on SMR ERD. Motor learning has been associated with changes in both ERD and ERS

underlying these variabilities is key to further improve NF success and thus the learning, improving and re-learning of motor skills. Technical factors that could account for these variabilities have been investigated in depth. Here, we focus on what we call context factors. The Webster-Merriam dictionary defines context as ‘the interrelated conditions in which something exists or occurs’ (<https://www.merriam-webster.com/dictionary/context>). Borrowing from this basic definition, we define context as the interrelated conditions in which (NF) motor tasks occur. Context factors can be relatively stable and long-term in that they cannot or would normally not change for an intervention period. Long-term context factors can be subdivided into factors regarding the individual (e.g. age, gender, personality or capability to perform the movement) and factors regarding the intervention (e.g. social context, environment, NF implementation, see Fig. 1). Context factors can also be short-term in that they can change from session to session (e.g. time of intervention in relation to time of sleep, circadian rhythm, nutrition, physical exercise or interference tasks) or even within a session (e.g. state motivation, attention and stress, experimenter gender). In this narrative review, we will give a brief overview of recent literature on such context factors. We will put special emphasis on MI NF, with the NF based on spectral neural signals measured with the electroencephalogram (EEG, see Table 2 for a summary of references from 2017 onward). Yet, despite the focus on MI NF, most context factors will be equally relevant for related domains.



**Fig. 1** Levels of context factors and their interactions. Differentiated is between long-term factors (dark blue) that act at the level of the individual or of the intervention, and short-term factors (light blue), with levels before/after and during a session. Factors can interact within levels (arrows top left) and between levels (arrows top right). Examples for interactions could be ‘Experimenter gender’ and ‘Acute stress’ within level, and ‘Declarative interference’ and ‘Acute stress’ between level. MI NF is under the influence of both, individual factors, and the consequences of within- and between-level interactions (bottom arrows)

**Table 2** Overview and summary of MI/NF papers from 2015 to 2000

Reference	Main task	Context factor/variable	Subjects (#, age)	Performance measure	Main finding
<i>Long-term factors: individual</i>					
Braun et al. 2017 [6]	Left- or right-hand MI (flexion–extension)	Capability to perform	Stroke: $N = 20$ (9 women) mean = 59.1y (SD = 9.9y) Control: $N = 20$ (9 women) mean = 60.1y (SD = 7.7y)	ERD (8–30 Hz), classification accuracy	Although MI abilities may be impaired after stroke, most patients retain their ability for MI/NF. Performance in the different MI measures did not strongly correlate
Jeunet et al. 2015 [7]	Left-hand MI (movement is chosen by the participant)	Personality	$N = 18$ (9 women), mean = 21.5y (SD = 1.2y)	Classification accuracy	The importance of spatial abilities and personality traits for MI/NF performance is highlighted
Zich et al. 2015 [8]	Left- or right-hand MI (repeated thumb abductions)	Age	Younger: $N = 39$ (19 women) mean = 23.6y (SD = 2.7y) Older: $N = 36$ (19 women) mean = 62.7y (SD = 5.7y)	ERD (8–30 Hz), classification accuracy	Older adults showed reduced lateralisation and reduced classification accuracies. EEG/NF enhanced task-related activity independently of strategy and age
Zich et al. 2017 [9]	Left or right MI (repeated thumb abductions)	Age	Younger: $N = 19$ (9 women) mean = 24.4y (SD = 2.7y) Older: $N = 18$ (10 women) mean = 62.6y (SD = 5.7y)	ERD (8–30 Hz), HbO, HbR	ERD and HbR were less lateralised in older adults. EEG/NF enhanced task-related activity in both older and younger adults. Significant modulation correlations were found between ERD and hemodynamic measures
<i>Long-term factors: intervention</i>					
Braun et al. 2016 [10•]	Right-hand MI (flexion–extension)	NF implementation	$N = 25$ (9 women) (20–30y)	ERD (10–25 Hz), Classification accuracy	Promoting effect of robotic hand embodiment in subjective, behavioural, electrophysiological, and electrodermal measures
Darvishi et al. 2017 [11•]	Left or right MI (four-finger flexion)	NF implementation	$N = 10$ (4 women) (24–40y)	ERD (8–13 Hz, 16–26HZ), Classification accuracy	Compared to visual feedback, proprioceptive feedback yields stronger and more consistent ERD and higher classification. These effects are more pronounced in the beta frequency range than in the alpha frequency range

Table 2 (continued)

Reference	Main task	Context factor/variable	Subjects (#, age)	Performance measure	Main finding
Daeglau et al. 2020 [12]	Walking MI	Social	N = 25 (14 women), mean = 24.9y (SD = 2.9)	ERD (8–30 Hz)	No difference between the competitive multi-user condition and the single-user condition, but considerable inter-individual differences regarding which condition yielded a stronger ERD
Pichiorri et al. 2015 [13•]	Left- or right-hand MI (finger extension, grasping)	NF implementation	Stroke NF group: N = 14 mean = 64.1y (SD = 8.4y) Stroke control group: N = 14 mean = 59.6y (SD = 12.7y)	Fugl-Meyer Assessment, Medical Research Council scale for muscle strength, National Institute of Health Stroke Scale, oscillatory activity and connectivity at rest (theta, alpha, lower beta, upper beta, gamma)	NF group has a significantly higher probability of achieving a clinically relevant increase in the FMA score. FMA improvements correlated with the changes at rest in ipsilesional intrahemispheric connectivity in the alpha and beta band
Pillette et al. 2020 [14]	Left-hand MI (movement is chosen by the participant)	Social	N = 28 (14 women) mean = 21.2y (SD = 1.6y)	Classification accuracy	Classification accuracy did not differ between the group with and the group without a learning companion. Non-autonomous people benefit from a learning companion
Vukelic and Gharabaghi 2015 [15••]	Right-hand MI (opening)	NF implementation	N = 11 (4 women) mean = 25.8y (SD = 3.1y)	Classification accuracy, ERD (14–24 Hz), functional connectivity	Proprioceptive feedback yields higher skill, lower variability in beta modulation, and functional coupling of remote beta and theta band activity
Zich et al. 2015 [10•]	Left or right MI (hand sequential finger tapping)	NF implementation	N = 24 (11 women) mean = 23.9y (SD = 2.4y)	ERD (8–30 Hz), fMRI activity, Classification accuracy	ERD correlates with fMRI activation in the contralateral sensorimotor areas, whereas a lateralised fMRI pattern did not necessarily go along with a lateralised EEG pattern
Zich et al. 2015 [16]	Left or right MI (hand sequential finger tapping)	Environment	N = 16 (11 women) Mean = 25.1 (18–32y)	ERD (8–30 Hz), Classification accuracy	Individualised mobile EEG enables high-quality and frequent training in daily life environments. ERD lateralisation and classification accuracy increase over three training days

**Table 2** (continued)

Reference	Main task	Context factor/variable	Subjects (#, age)	Performance measure	Main finding
Zieh et al. 2017 [17]	Left- or right-hand MI (power grip)	Environment	Stroke: $N=3$ (71y [women], 51y, 56y)	Behaviour, ERD (8–30 Hz), fMRI activity, fractional anisotropy	EEG activity induced by MI of the affected hand became more lateralised over the four-week training in all three patients. The patient with a significant functional change also showed increased white matter integrity and a substantial clinical improvement of upper-limb motor functions
<i>Short-term factors: before and after a session</i>					
Daeglau et al. 2020 [18]	Left- or right-hand MI finger tapping	Sleep	$N=53$ (41 women) mean = 25y (SD = 3.3y)	ERD (8–30 Hz)	ERD was unaltered by declarative interference and sleep
Meng et al. 2017 [19]	Left- or right-hand MI as well as left and right-hand MI simultaneously (no specific movement stated)	Nutrition	$N=26$ (11 women) mean = 23y (SD = 4.1y)	Resting state EEG (10–26 Hz) Online BCI performance (percent valid correct)	Caffeinated drinks, but not sugary drinks, before the BCI session reduce baseline power, while online BCI performance was unaffected
Vourvopoulos et al. 2017 [20]	Left- or right-hand MI (e.g. mental grasping, throwing, waving)	Circadian rhythm	$N=34$ (17 women) range: 18–33y	Power spectral density (1–3; 4–7; 8–12; 12–30; 25–90 Hz) Engagement Index	Increased gamma (but not mu and beta) band power and ‘Engagement Index’ values for afternoon compared to morning and evening sessions
<i>Short-term factors: during a session</i>					
Roc et al. 2019 [21]	Increasing height of feedback bar, no specific instructions on how to achieve this Increasing length of feedback bar by MI of right- and left-hand movements without restrictions on the imagined movement	Experimenter gender	$N=59$ (29 women) mean = 29y (SD = 9.3y)	Progress of quality-weighted classification accuracy across NF runs 3–6	Interaction between participant gender, experimenter gender, and progress over runs; indication that female experimenters have positive influence on progress
Wood and Kober 2018 [22]	Increasing height of feedback bar, no specific instructions on how to achieve this	Experimenter gender	$N=142$ (48 women), mean = 23y (SD = 3.2y)	Increase in SMR power (12–15 Hz) across 6 NF runs	Of all possible experimenter gender/participant gender combinations only female participants with female experimenters not able to upregulate SMR



## Long-term Factors: Individual

Normal *aging* is accompanied by anatomical and functional changes and MI NF performance is no exception to this. Older adults perform MI as vividly as younger adults [23–25]; however, MI quality [24] and accuracy of estimating temporal and spatial characteristics of MI are altered (explicit MI: [8, 9], implicit MI: [26]). These age-related behavioural changes are accompanied by neurofunctional changes, i.e. more widespread and symmetric activity in older adults [27], which are in line with the HAROLD model [28]. Similar results could be observed for MI NF [29, 30]. Moreover, when the neural feature which serves as the basis for the NF is subject to age-related changes the MI NF performance is likely altered as well [29].

Regarding *gender*, while men show better target abilities in gross movements [31], women are better in fine movements [32]. MI NF comprises mostly small hand movements, which is why women might have an advantage. However, MI NF comprises additional mental and technical elements that can have an effect. Regarding the mental element, for MI, no gender difference has been observed [7, 25]. However, regarding the technical element, it has been found that control beliefs while dealing with technology [33], which are generally higher in men [33], correlate negatively with MI NF performance ([34], but see also [35]). Witte and colleagues interpret their findings as follows: individuals with strong control beliefs try harder to control the NF and thus activate potentially interfering resources. This is in line with a finding on *personality* traits indicating a negative relationship between MI NF performance and tension [36]. The same study reported that MI NF performance was positively related to self-reliance and abstractness. However, the correlation between personality traits and MI NF performance was too small to justify the inclusion of personality traits in the prediction model for MI NF performance [37].

*Expertise and capability to perform* the to-be-imagined movement constitute further context factors. Compared to experts, novices recruit additional resources during MI ([38], for reviews, see [6, 39]), which has been linked to increased cognitive demand [40]. In healthy individuals, short-term limb immobilisation led to selective impairment of MI ability [41, 42]. Post-stroke some studies found MI, in general, to be altered [43, 44•], while others found specific aspects of MI to be altered [12, 14] or no alterations [16, 17]. Interestingly, Braun et al. [44•] found that although MI abilities may be impaired after stroke, most patients retain their ability for MI NF.

## Long-term Factors: Intervention

The number of individuals participating in the same session constitutes its *social context*. Although practicing in a group has several advantages, MI NF is traditionally conducted

alone and only a few studies investigated the effect of social context on MI NF. Initial reports suggest that, compared to a single-user and a competitive multi-user condition, a collaborative multi-user condition is generally more enjoyable and motivating [45]. However, inter-individual differences exist concerning which social context yields stronger neural activity during MI NF [10•]. Considerations on the importance of social context have inspired the development of a personalised emotional agent for NF [11•].

MI NF is primarily conducted in laboratory-based environments. While this instigates methodological rigour, MI NF at home enables, regarding the context factor *environment*, familiar surroundings and no need to travel. These are key elements of the so-called home advantage, which has a positive effect in sport and probably also for MI NF. While technical aspects of laboratory- and home-based settings have been compared [3] the impact of the context factor environment on MI NF success has not been formally studied yet. Despite this gap, MI NF at home gains popularity [15••], probably also because it is less cost-intensive, more inclusive and enables more frequent and more ecologically valid training [46].

While some aspects of the NF will be adapted on a session-to-session basis (e.g. spatial and temporal properties of the extracted EEG signals, classifiers for the NF), the overall *NF implementation* is likely to be constant throughout the training. While MI NF can be based on nearly any recording technique or combination of techniques (so-called hybrid approaches, e.g. EEG-fNIRS, EEG-fMRI), EEG-based NF is most common. Crucially, for EEG it has been shown that not every individual will show the neural feature which serves as the basis for the NF. These cases would likely benefit from hybrid implementations or a complete switch of recording technique [47]. Regarding the feedback modality, proprioceptive NF yields stronger and less variable task-related modulation in power than visual NF [13•, 48]. This is in line with the notion that realistic and embodyable NF (robotic hand: [49]; virtual environment: [50]; electrical stimulation: [51]) is advantageous. For both, visual and proprioceptive NFs, it has been shown that positive feedback is preferable [52, 53].

## Short-term Factors: Before and After a Session

It has been suggested that *experience* with a given movement is necessary for correct and vivid MI [54–56]. Yet, often, novel movements with which participants have only limited experience are used (for a review, see [57]). In a recent study, we aimed to evaluate the effect of extended ME practice in a visuo-motor task. We did not find evidence that ME practice leads to a stronger subsequent MI-induced ERD of the same movement in comparison to no prior ME practice [58]. This contrasts with previous studies reporting priming

effects (ME on MI: [56]; MI on ME: [57, 58]), which we currently interpret, as an indication that already rather small differences between setups can lead to deviant or opposing findings. To only name two aspects which may have prevented measurable behavioural and neural gains following MI [58] in our study, we did not include a preparation phase before the beginning of each trial, and the motor task was slightly more complex than in other studies. Further research is necessary to shed light on the specific relevance of these and other factors for MI NF.

*Sleep* is a key component for the offline phase (i.e. after practice: [59, 60]) of motor learning, improving and re-learning (for a review, see [61]). Several studies on motor skill acquisition have shown beneficial effects of sleep following motor skill practice on subsequent motor performance (for an extensive review, see [62]). However, this well-established finding was challenged lately, for instance by evidence that supposedly sleep-related performance gains are not exceeding performance levels already achieved shortly after a practice session, e.g. [63–66]. This ‘early boost’ may represent an offline performance gain, and can be measured around 5–30 min after motor (imagery) practice and then declines over the next 4–12 h of wakefulness [18, 67, 68]. More recent studies indicate differences regarding the practice modality, that is, MI or ME and task complexity for gains following a night of sleep. Freitas and colleagues found no offline gain in ME performance after combining ME practice and sleep, but when MI practice was followed by sleep, ME performance further improved compared to performance right after practice [69]. MI practice resulted in an additional performance increase after sleep compared to consolidation over the day but only for a complex movement sequence [70]. The finding that the effects were restricted to the complex movement is partially in line with recent findings on MI NF performance on a simple MI task that neither indicate the presence of an early boost nor of sleep-related performance gains [71]. Interestingly, in contrast to the relatively rich body of research on sleep, the impact of sleep deprivation on motor performance remains unclear [72].

In addition to the effects of a full night of sleep, *daytime naps* have also been investigated lately. For ME practice, Backhaus and colleagues found that short daytime naps did not have a positive impact on offline learning and sleep-dependent consolidation for both explicit motor sequence and motor adaptation practice tasks in older adults, but rather led to performance deterioration [73]. In contrast, a daytime nap after MI practice was found to improve motor performance [74]. Debarnot and colleagues [75] found adverse effects of subsequent *declarative interference*, that is, of performing tasks drawing on declarative memory, on the positive effects of MI practice on ME, both over intervals of sleep and wakefulness. Adverse effects have been reported to be less sustainable for ME practice, where

motor consolidation is impaired by declarative interference over wakefulness but recovers over a period of sleep [76]. However, no evidence for any adverse effect of various verbal and non-verbal declarative interference tasks on ME task performance was found in a more recent study [77]. In line with the latter, we found no evidence for any impact of declarative interference on MI NF performance, neither over wakefulness nor after a night of sleep [71].

*Circadian rhythm* and *chronotype* have been studied for ME, MI and MI NF. Scheduling practice sessions according to athlete’s circadian preferences yielded significantly better ME performance [78]. Also, learning new movement sequences in the morning induces an increase in corticomotor excitability in the primary motor cortex that is absent when learning new sequences in the evening ([79], but see [80]). For MI time (i.e. time to imagine a given task) and MI chronometry (i.e. temporal congruency between ME and MI), Debarnot and colleagues found modulations based on circadian rhythm, but rather unsystematic and task-dependent [20]. This finding was supported [81] and extended to the factor motor imagery quality [82]. In an MI BCI gaming paradigm significantly increased gamma, but not mu and beta, band power and increased ‘Engagement Index’ values have been reported for afternoon compared to morning and evening sessions [83].

Insights on the role of *nutrition/food intake* on motor performance come, for instance, from fasting: while two days of strict fasting in obese women had no effects on handgrip strengths and psychomotor coordination [19], a period of Ramadan fasting reduced agility, speed and reaction time performance for male tennis players [84]. This is in line with a recent meta-analysis showing that dehydration impairs performance in tasks involving attention, executive function and motor coordination when water deficits exceed 2% body mass loss [85]. Moreover, while caffeinated drinks, but not sugary drinks, before the BCI session were found to reduce baseline power in the mu and beta frequency range, online BCI performance was unaltered [86].

*Physical exercise* unrelated to the motor task under investigation expedites motor learning, improvement, and re-learning and learning-related neural activity [87, 88]. This also holds for the MI SMR within the mu frequency range [22]. Furthermore, a progressive muscular relaxation (PMR) intervention before MI NF was found to boost NF performance [21].

## Short-term Factors: During a Session

Across a wide range of domains, it has been shown that in experiments with humans, *experimenter gender* can have an influence on experimental findings [89]. Little

surprisingly, this also holds for MI NF. Wood and Kober [90•] trained male and female participants by either male or female experimenters and found that female participants trained by female experimenters did not show a gain in the NF signal. Another study however indicated an overall positive effect of female experimenters on MI NF performance in male participants, and mixed effects of experimenter gender on performance in female participants [91]. Thus, though in general, women seem to perform better with male experimenters and vice versa [89], for MI NF performance, the direction of the effect appears less clear. A factor contributing to the latter could be how the purpose of the NF session is—inadvertent or intended—perceived by the participant, i.e. as technologic or therapeutic [90•]. The generally seen opposite-sex performance benefit has been attributed to an aggregation of moderate levels of psychosocial stress and the heightened reward potential of opposite-sex interactions [92]. The findings by Wood and Kober [90•] and Roc et al. [91] are both partially in line with this. Recent evidence from the motor learning domain underline however that also detrimental opposite-sex effects can occur [92, 93], indicating that in some setups, psychosocial stress levels induced by opposite-sex experimenters can become so high that performance drops. *Acute stress*, experimentally induced through pain and social evaluation, has been found to reduce performance in implicit but not in explicit MI [94]. As MI NF relies on explicit MI, it can be expected that it is also sensitive to acute stress, though this has not been tested yet. For motor learning, effects of acute stress have also been reported, but with diverging outcomes. One recent study, inducing stress through pain and social evaluation, found no effect of acute stress on initial motor performance, training gain and motor memory consolidation at the group level. The acute stress group data indicated however a negative correlation between overnight gains in performance and the stress-induced cortisol level [95]. This contrasts with a study in which stress and anxiety were induced through a computerised mental arithmetic task and whose results indicate positive effects of acute stress on training gain and retention [96].

Adding NF to MI can raise or keep up motivation, and, as discussed above, it is assumed that this depends, among others, on the NF implementation. The motivation added by the NF is met by the general motivation of a participant to participate. Though the motivation to participate in a MI NF study is most likely derived from several sources, for the prototypical healthy participant, it will be predominantly extrinsically driven, with money or course credits as main rewards. For patients, such external rewards will be of comparatively little importance. Their motivation will be much more intrinsically driven, for instance by the wish to learn about new

therapeutic options or by the hope to improve function. Yet even in participants with a strong intrinsic motivation to participate such as chronic stroke patients, *state motivation*, that is, the motivation for a given session, varies between sessions [15••]. Several older studies with healthy participants indicate that state motivation can have an influence on MI NF performance [97–99]. In these studies, state motivation was operationalised along several dimensions. The dimensions ‘perceived challenge’ and ‘interest’ correlated positively with performance. For the dimension ‘fear of incompetence’, overall, a negative relationship was found [97–99]. A longitudinal study with patients suffering from amyotrophic lateral sclerosis (ALS) also reported a positive correlation between ‘perceived challenge’ and performance, but only for one of six patients and no significant correlation for the remaining five patients [100]. This and related findings for stroke patients [97] suggest that for patients, the link between state motivation and MI NF performance might differ from healthy participants. We found no recent literature following up on these earlier reports on motivation though, corroborating this observation. Yet irrespective of this, it is a fact that to some degree MI NF training will have to put up with fluctuations in motivation, as reasons can be personal and entirely unrelated to the NF training in itself. At the same time, experimenters or therapists should also be open to the possibility that their conduct can have an influence on state motivation and thus, potentially, on NF performance. This is suggested by the finding that a motor learning setup in which the experimenter supports the human psychological need of relatedness [101] by emphasising caring and interest in the participant’s experiences improves not only motivation and positive affect but also motor learning and retention [102].

The aspects discussed so far can change between sessions but are probably rather stable within a session. Other aspects, such as the ability to focus on the task or *attention*, are likely to change on a shorter time scale, that is, from trial to trial or as a function of time within a session. To learn more about these fluctuations and how they affect MI NF or BCI performance, the period before the start of the actual MI task has been mined for information. While an early study successfully predicted trial-by-trial performance of an SMR-based MI NF with fluctuations in gamma activity [103], subsequent studies derived predictors from various combinations of at least three frequency bands, including the delta, theta, alpha, beta and gamma bands [104, 105]. Importantly, the best-performing combination of predictors was found to differ between participants [105]. The individuality of best-performing predictors is in line with findings on predicting ME performance based on spectral pre-trial EEG activity [106].



## Prospects and Concluding Remarks

In this narrative review, we highlight a range of long- and short-term context factors summarised in Fig. 1 that can influence the learning, improvement and re-learning of motor skills. We primarily focused on MI NF, whereby this was supplemented by literature from related domains, such as MI without NF and ME. Nevertheless, this review is not exhaustive and other context factors will certainly also play their role. One such factor constitutes other additional neuromodulation techniques, such as pharmacological interventions (e.g. GABAB receptor agonist on ME learning [107] or brain stimulation e.g. transcranial direct current stimulation (tDCS) and MI NF: [108–111] or transcranial alternating current stimulation (tACS) and MI NF: [112]), if applied before/after or during the session.

For several of the context factors reviewed, contradictory results were found. One important aspect of this may be the nature of the motor task. A wealth of motor tasks is used in research, and, in other frameworks, task variability served as an explanatory variable for variability in results, both across individuals and studies e.g. [20, 70, 73]. On the other hand, it is also conceivable that the effect of context factors is largely independent of the motor task and that the differences in findings have another origin, such as the interaction between context factors or individual preferences (cf. section social context) and/or individual physiological differences [113, 114]. Future research will have to investigate the merits of this case.

With this first review on context factors in MI NF and related domains, we focus on the main effects, i.e. the independent and direct influence of each factor. Beyond that, however, interactions can occur within each level, e.g. between two or more long-term factors, and, across levels, e.g. factors that are relevant before the session can interact with factors that are relevant during the session. We believe that from considering main effects and interactions our understanding of the impact of context factors on MI NF performance and related domains will greatly benefit.

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## References

Papers of particular interest, published recently, have been highlighted as:

● Of importance

●● Of major importance

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