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The influence of motivation and emotion on sensorimotor rhythm-based brain–computer interface performance

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Abstract

While decades of research have investigated and technically improved brain–computer interface (BCI)-controlled applications, relatively little is known about the psychological aspects of brain–computer interfacing. In 35 healthy students, we investigated whether extrinsic motivation manipulated via monetary reward and emotional state manipulated via video and music would influence behavioral and psychophysiological measures of performance with a sensorimotor rhythm (SMR)-based BCI. We found increased task-related brain activity in extrinsically motivated (rewarded) as compared with nonmotivated participants but no clear effect of emotional state manipulation. Our experiment investigated the short-term effect of motivation and emotion manipulation in a group of young healthy subjects, and thus, the significance for patients in the locked-in state, who may be in need of a BCI, remains to be investigated.

KEYWORDS

brain-computer interface, electroencephalogram, emotional state, motivation, psychological variables, sensorimotor rhythm

1 | INTRODUCTION

Brain–computer interfaces (BCIs) allow for device control without motor involvement as they translate brain activation into output signals for communication or environmental control applications (Wolpaw & Wolpaw, 2012). One common BCI input signal is the endogenously modulated sensorimotor rhythm (SMR; Pfurtscheller & McFarland, 2012) appearing in the alpha band from 8 to 12 Hz (μ rhythm) and the beta band from 18 to 25 Hz over sensorimotor cortices (SMCs, M1/S1; Neuper & Pfurtscheller, 2010). In a relaxed state, SMR is synchronized (event-related synchronization [ERS]) but desynchronizes as a result of motor movement or imagery (event-related desynchronization [ERD]; Pfurtscheller, 1992). ERD within a certain frequency domain and at specific electroencephalogram (EEG) channel locations (features) corresponds to a variable degree to the performed motor imagery (MI) task, which is expressed with the *r*-squared value (Blankertz et al., 2007; Graimann et al., 2002; Lotte et al., 2007). A typical SMR-BCI task consists of steering a cursor from the left margin of a computer screen to a target area appearing at the top (e.g., SMR ERD) or bottom (e.g., SMR ERS) of the right margin of a computer screen, thereby instigating binary control via MI. Successful SMR-BCI control was demonstrated in healthy participants (Blankertz et al., 2010; Hammer et al., 2012; Jeunet et al., 2016; Zhang et al., 2015) and individuals with amyotrophic lateral sclerosis (ALS) or other neurological diseases

(Gu et al., 2009; Holz et al., 2013; Kübler et al., 2005; Neuper et al., 2006; Nijboer, Sellers, et al., 2008; Perdikis et al., 2018).

However, about 20% of SMR-BCI end users are unable to control an SMR-BCI (Blankertz et al., 2010). Neurophysiological (e.g., Blankertz et al., 2010; Halder et al., 2013) and psychological predictors of SMR-BCI performance were investigated (e.g., Botrel et al., 2017; Hammer et al., 2012, 2014; Jeunet et al., 2016), and motivation was found to correlate with BCI performance (Käthner et al., 2013; Kleih & Kübler, 2013; Kleih et al., 2010, 2011; Nijboer et al., 2010; Nijboer, Furdea, et al., 2008). Nijboer and colleagues (2008) found the motivation component *incompetence fear* to be negatively correlated with SMR-BCI performance while *mastery confidence* was positively correlated with performance. Kleih et al. (2013) replicated these results and showed that increasing *fear to fail* correlated negatively with performance, not only in healthy participants but also in patients after stroke. Therefore, performance expectation as a motivation component may influence learning success in SMR modulation and, thus, BCI control. Jeunet et al. (2016) emphasized the role of performance expectations influenced by, for example, computer anxiety. The authors assume computer anxiety to possibly appear when end users are confronted with unfamiliar technology. The feeling of being overwhelmed by the technology might lead to a decrease in expected self-efficacy and negatively influence BCI learning. In their cognitive model of SMR-BCI user training, Jeunet et al. (2017) argued that motivation in SMR-BCI operation may influence attention, which is a prerequisite for self-regulatory processes. Therefore, high motivation should lead to higher attention and, thereby, to better BCI performance. In this article, we focus specifically on motivation as one psychological factor possibly influencing SMR-BCI performance. First suggestions on how to integrate psychological motivation theory and BCI research do exist for SMR-based BCIs (Jeunet et al., 2017; Kleih & Kübler, 2016) as well as for BCI systems based on evoked potentials (Kleih & Kübler, 2013, 2014).

With the current study, we aimed at further substantiating the role of motivation for BCI-control. As motivation might be influenced by a person's emotional state which in turn, may affect behavior (Gendolla, 2000; Hirt et al., 1996), we also addressed the effect of emotional state. Inducing positive emotion by film clips had beneficial effects on performance in creative problem solving (Isen et al., 1987). Positive affect induced by word stimuli lead to increased response speed, performance and higher prefrontal activation as compared to induced negative affect (Herrington et al., 2005). Negative emotional state deteriorated cognitive functions such as working memory (e.g., Curci et al., 2013) and was hypothesized to lead to reduced self-regulation. This might cause reduced task performance as attentional resources are not focused on the task but instead on the emotion inducing event (Baumeister & Heatherton, 1996). In a BCI context, negative emotion might hinder self-regulation necessary to comply with the task and lead to reduced performance. However, increasing motivation may attenuate the detrimental effect of negative emotion and alleviate attention allocation toward the BCI task. To test these assumptions and the applicability of the presented effects of motivation and emotional state to a BCI context, we performed the herein presented study. We hypothesized firstly that motivated participants would perform better with an SMR-BCI (percentage of correct trials, Hypothesis 1a), as indicated by higher r-squared values (Hypothesis 1b) as compared to unmotivated participants, irrespective of their emotional state. As we expected an effect of emotional state, even though less prominent as compared to motivation, we hypothesized secondly best performance in motivated participants in neutral emotional state and worst performance in unmotivated participants in negative emotional state (Hypothesis 2a). We also expected highest r-squared values in the motivated group in neutral emotional state and lowest values in the unmotivated group in negative emotional state (Hypothesis 2b).

2 | METHOD

2.1 | Participants

Forty-two healthy volunteers participated in this study, all naïve to BCI training. Seven participants had to be excluded from analysis due to strong movement artifacts ($n = 3$), incompliance ($n = 1$) or technical problems in data acquisition ($n = 3$), leaving $n = 35$ subjects for further investigation. Average age was 24.22 ($SD = 3.51$, range: 19–36, $n = 15$ male). All participants received 8 € per hour compensation and signed informed consent. The study was reviewed and approved by the Ethical Review Board of the Medical Faculty, University of Tübingen.

2.2 | Manipulation and stimuli

2.2.1 | Motivation

To our knowledge, there are no studies investigating the effect of monetary reward on the SMR. However, monetary reward was chosen in this study for motivation manipulation because it has been shown to affect other brain responses (Goldstein et al., 2006; Wu & Zhou, 2009; Yeung & Sanfey, 2004) and to increase motivation in a BCI context (Kleih et al., 2014). We therefore trained one group who received monetary reward for each successful brain activation and one group who did not receive such reward. To support

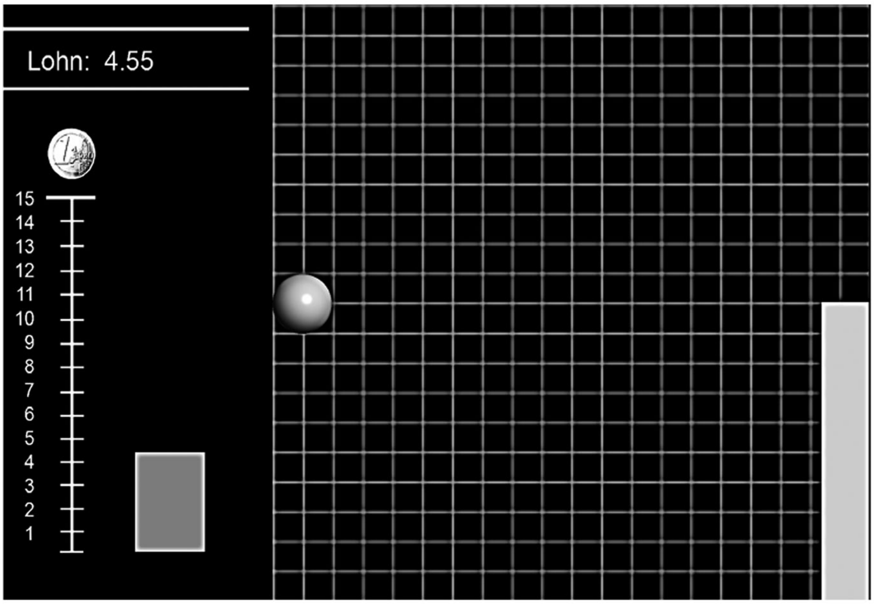


FIGURE 1 SMR-BCI training screen. The cursor had to be steered to the highlighted target area (lower right of the screen) by motor imagery (see Section 2.4). On the left, the reward bar indicated how much extra money in € the participant had earned ranging from 1 € to 15 € in the motivated group. The counter bar increased by 5 cents with each successful trial

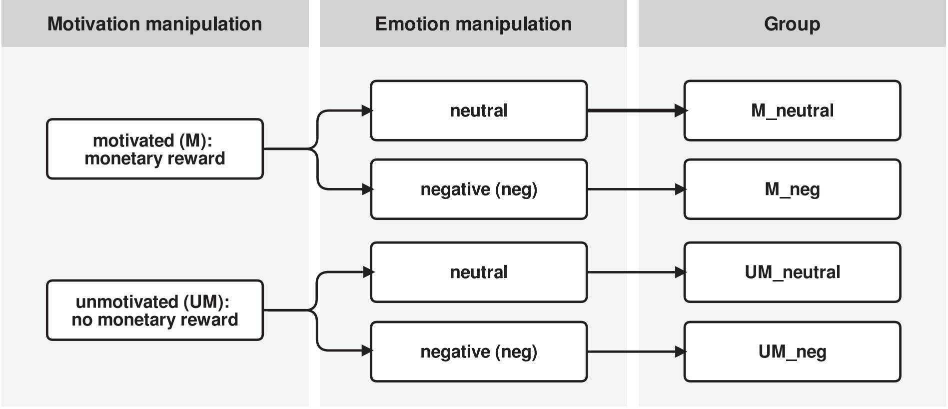


FIGURE 2 The study design with motivation and emotional state as independent variables

learning by providing salient and consistent feedback of reward, a reward bar overlay coded in Python[1] using the pygame[2] library was implemented into the BCI feedback screen (see Section 2.4). Successful cursor control resulted in a monetary reward increase immediately visible for the BCI user throughout the entire duration of the experiment (see Figure 1).

2.2.2 | Emotional state

We induced negative and neutral emotional states. We decided for neutral emotional state because we assumed such state to represent a "baseline". We chose negative emotional state as we hypothesized stronger effects on BCI performance as compared to positive emotional state.

To manipulate emotional state, we used movie scenes (Macht & Mueller, 2007) and pieces of music. We chose a movie scene from "The Champ" (2:51 min, Lovell & Zeffirelli, 1979) which was evaluated as inducing negative emotion by Gross and Levenson (1995). In this movie scene, a boy realizes that his father had died. For neutral emotional state induction, a scene from a documentary about the production and use of copper (2:02 min; Macht & Mueller, 2007) was chosen. To preserve induced emotional state for the entire BCI experiment (Coen et al., 2009), we employed two pieces of music. For negative emotional state we used a part of the prelude of the third act from "La Traviata" by Verdi (1984; 2:00 min) while for neutral affect we selected a piece from a concert for three pianos d-moll (BWV 1063; 2:00 min) by Beroff et al. (1984). The pieces were evaluated for emotion

[1]Python Software Foundation. Python Language Reference, version 2.7. Available at http://www.python.org

[2]www.pygame.org GNU LGPL version 2.1.

induction in the desired direction (Schaefer, 2009) and played in loop during the experiment.

2.3 | Study design

A mixed design was implemented with the independent variables motivation (motivated vs. unmotivated) and emotion (neutral vs. negative emotion) which served as between-subject variables. Each participant completed three sessions of BCI training. These sessions served as within-subjects factor. Participants were randomly assigned to one of the resulting four groups (see Figure 2). Dependent variables were BCI performance (percentage of correct trials) and *r*-squared values from the feedback period duration.

2.4 | Material

2.4.1 | Motivation

For the manipulation check, we used a visual analogue scale (VAS). Motivation had to be specified on a 10-cm line with 0 indicating not motivated at all and 10 very motivated. To describe participants' motivational state in more detail, we assessed the Questionnaire for Current Motivation in BCI use (QCM-BCI, Rheinberg et al., 2001; adapted for BCI use by Nijboer, Furdea, et al., 2008). The QCM-BCI comprises 18 items representing four motivation components *mastery confidence*, *incompetence fear*, *challenge* and *interest* to be rated on a 7-point Likert scale.

2.4.2 | Emotion

To quantify the emotional state before the manipulation, we used the German version of the *Center for Epidemiological Studies Depression Scale—CES-D* (Allgemeine Depressionsskala [ADS], Hautzinger & Bailer, 1993). The ADS short version (ADS-K) comprises 15 items to be rated on a 4-point Likert scale ranging from 0 (rarely or never) to 3 (most or always). A score above 23 indicates clinically relevant symptoms of depression.

For the manipulation check, we used the Self-Assessment Manikin (SAM). With the SAM affective reactions to diverse stimuli can be assessed and a relation between SAM responses and physiological responses was demonstrated (Bradley & Lang, 1994). The SAM is a picture-based 9-point rating scale to assess the affective state with the categories of valence, arousal, and dominance. We assessed valence and arousal. The figure best representing a person's current emotional state had to be marked (1 = very sad and 9 = very happy and 1 = very calm and 9 = very aroused).

2.5 | Procedure

Participants were seated approximately 70 cm from a 43-cm monitor and answered the ADS-K. Motivational state was assessed with the QCM-BCI and the VAS motivation (t1). Emotional state was assessed using the SAM valence and arousal (t1). Electrodes were fixed for EEG assessment. During BCI system calibration, participants observed a white screen on which three arrows were presented. Participants were instructed to kinesthetically imagine movements with hands or feet as indicated by the arrows (arrow to the left = left hand, arrow to the right = right hand or arrow pointing downward = feet). An arrow was presented for 4 s, pre-stimulus and post-stimulus duration was 750 ms. Participants completed 4 runs of 75 trials each, resulting in a total of 100 trials per imagery condition (left hand, right hand, feet). The two MI conditions which indicated the highest difference between each other were chosen for feedback. The electrodes and the corresponding frequencies for which ERD was strongest were chosen for classification in the online training sessions.

Before the online feedback session, participants were randomly assigned to one of the four groups. Rewarded participants could earn 5 cents for every successful trial (motivated) which added up to 15 € extra reward at most per session. This group was informed by the experimenter about the opportunity to earn extra money prior to the first BCI session. Participants in the unmotivated group could not earn any extra money. For emotion manipulation, participants watched a neutral or sad video. Before starting the SMR-BCI feedback session, VAS motivation and QCM-BCI were assessed again as well as the SAM for valence and arousal (t2). Then participants listened to sad or neutral music with Sony MDR-15 headphones during the whole SMR-BCI session.

Participants had to control a constantly moving cursor from the left margin of the screen into a colored area which either appeared on the top or the bottom of the right margin of the screen (see Figure 1). By imagining one of the two chosen movements, the cursor was steered upward to the top target area while imagining the other steered the cursor into the bottom target area. In the motivated group, a money counter was displayed next to the BCI cursor control screen and every successful target hit increased the red bar for another 5 cents. The totally earned amount was displayed and the increase of the bar was visible throughout the session (see Figure 1). This setup per se was also part of the motivation manipulation while performing the SMR-BCI session as successful ERD was immediately positively reinforced and could increase motivation. The space on which the money bar was displayed in the motivated groups was blank in the unmotivated groups.

During online BCI sessions, participants performed three training blocks each comprising four runs of 25 trials, resulting in a total of 300 trials (150 for each imagery condition).

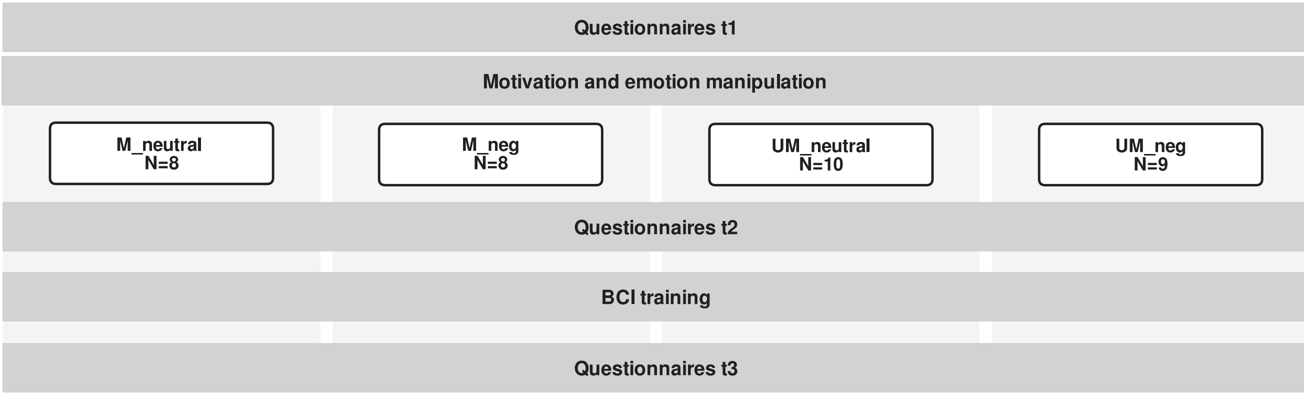


FIGURE 3 Emotion and motivation were assessed three times throughout the BCI training on each of the 3 training days. QS, questionnaires; t, time of measurement

After finishing the last block, emotion and motivation were assessed again with the VAS motivation and SAM (t3). Participants performed two more sessions on 2 days within 1 week at the same time of the day as the first session. Questionnaire assessment in sessions two and three was identical to the assessment in the first session. The experimental procedure is illustrated in Figure 3. After their third training session, we informed participants about the existence of four different groups.

2.6 | Data acquisition

Stimulus presentation and data collection were controlled by the BCI2000 software. We used Ag/AgCl electrodes at locations AFz, FC5, FC3, FC1, FCz, FC2, FC4, FC6, C5, C3, C1, Cz, C2, C4, C6, CP5, CP3, CP1, CPz, CP2, CP4, and CP6. Electrode positions were based on the modified 5–10 system of the American Electroencephalographic Society (Sharbrough et al., 1991). To record horizontal and vertical eye movement, EOG electrodes were placed next to the lateral canthi, between the hairline and the eye and above and below the left eye in line with the pupil. As due to unaware movements of the limbs while doing MI, EEG changes might be attributable to real movements instead of imagined movements, six electrodes for electromyography (EMG) were positioned. To properly identify electrode positions, we instructed participants to slightly move their hands and observed where muscle contraction on the *brachioradialis* and the *flexor carpi ulnaris* of both arms were most noticeable. On the lower leg, we placed one electrode above the *musculus tibialis anterior* and one on the *musculus gastrocnemius* where muscle contractions as a result of slight movement were most pronounced. Electrodes were referenced to the right and grounded to the left mastoid. The EEG was amplified with two synchronized 16-channel g.USB amplifiers (Guger Technologies, Austria). Sampling rate was 256 Hz. The 50 Hz noise was filtered with a notch implemented in the BCI2000 software. Data processing, storage, and stimulus presentation were controlled with an IBM ThinkPad laptop.

2.7 | Data classification and analysis

2.7.1 | Calibration

After the calibration session in which 100 trials per MI were obtained, the BCI 2000 Offline Analysis tool (BCI2000) was used to display the power and r-squared values of the power explained by target condition for each electrode × frequency feature between 0 and 30 Hz. For the feedback condition, the experimenter chose a feature with a frequency value between 9 and 25 Hz on an electrode somatotopically associated with the MI. To be chosen, the r^2 value needed to be maximum between the imaginary conditions (e.g., left versus right imagination) using the r^2 values displayed on a feature plot (x = frequency, y = channel, $z = r^2$) following the standard procedure for BCI2000 CursorTask, (BCI2000). Most of the time, C5, C3, or C1 were picked along right-hand MI; C6, C4 or C2 with left hand MI; Cz or CPz with feet. The selected features (e.g., electrode C3 at 11 Hz and C5 at 11 Hz) were then used for classification. Only feature weights contributing unequivocally to the same MI target, based on SMR location and *r*-square, value were selected and were given the same weight. For 11 participants, the experimenters chose two or three features instead of just one, but all were attributed the same weight in the classification process.

2.7.2 | Online feedback

A common average reference (CAR) filter was applied on EEG channels prior to data processing. During feedback, the autoregressive classifier output was calculated as the spectral amplitude of each features in 3 Hz bins centered on feature frequency during a 500-ms sliding window, updated every

TABLE 1 VAS motivation means (*M*) and standard deviations (*SD*) for the motivated group (Mo) and the unmotivated group (UM) in sessions 1 (S1), 2 (S2), and 3 (S3)

	Motivated group Mo			Unmotivated group UM		
	t1	t2	t3	t1	t2	t3
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*
S1	7.48 (1.12)	7.67 (1.43)	8.51 (1.04)	7.75 (1.47)	7.22 (2.16)	7.40 (2.21)
S2	8.07 (1.54)	7.77 (1.72)	8.31 (1.34)	7.50 (1.69)	7.46 (1.92)	7.17 (1.92)
S3	7.61 (1.77)	7.64 (1.27)	7.78 (1.79)	7.76 (1.41)	7.58 (1.45)	7.42 (1.74)

31.25 ms. The resulting values were all negatively weighted such that a reduction of amplitude caused by contralateral limb MI ERD would translate into an upward motion of the cursor. To translate the classifier's output in feedback control, its output was normalized using zero mean offsets and gains to unit variance. These normalization parameters were dynamically adjusted by BCI2000 in the first run of the first feedback session and used for all sessions.

2.7.3 | Offline analysis

For offline analysis, we analyzed the neurophysiological output of online feedback across the three sessions. We attempted to reduce artefacts contamination by applying a bandpass filter between 0.01 and 60 Hz and a Gratton et al. (1983) regression-based signal correction from Brain Vision Analyzer using EOG lateral (above the eye) and EOG horizontal (temple of the left eye). Signals were then spatially filtered using common average reference (CAR). The rest of the data analysis was performed with MATLAB© 2015b using Berlin-BCI toolbox functions (Blankertz et al., 2016). Noisy trials with excessive variance were removed using the according Berlin-BCI toolbox. For each trial, we selected the channels and bandpassed the signal at the frequency corresponding to each subject-specific feature (i.e., features used in the online classifier ±1 Hz). For each feature, we extracted the Hilbert's envelope of the signal with a 200-ms window for each sampling point of the 4-s windows of feedback control. The amplitude was baselined to the average amplitude of a 1-s interval before cue. Signed *r*-squared values of the amplitude for target versus nontarget were also calculated. Before entering statistical analysis, amplitude and signed *r*-squared output values during feedback presentation were averaged over features and feedback time for each trial.

Offline analysis revealed a technical error in BCI2000 operation causing 11.83% of all trials to be supported by run-wise unit variance-based adaptation, yet without any change to the classifier and its features. We investigated a possible relation between the amount of trials with adaptation a participant received and BCI performance (Spearman correlation and linear regression models including group assignment) and found no relation. These statistical tests were identically applied to the neurophysiological outcome variables ERD/ERS signal difference and *r*-squared, yielding no significant association. Therefore, we assume our manipulation to be valid and continued data analysis according to our hypotheses.

Questionnaire raw data were transformed to norm values when indicated. For statistical analysis, IBM SPSS 24® was used. Data were weighted to control for unequal numbers of participants in each group. The level of significance was set to alpha = .05. If not indicated otherwise, we calculated a mixed model for each training day. We used a 2 (motivated and unmotivated) × 2 (negative and neutral affect) repeated measures ANOVA for statistical analysis with time of measurement as within-subjects factor. In case Mauchly's test for sphericity was significant, we reported Huynh-Feldt corrected statistics. Normal distribution was tested using the Shapiro-Wilk test.

3 | RESULTS

3.1 | Manipulation check motivation

For the motivation manipulation check, we used a repeated measures ANOVA only in the motivated group as we only expected an increase of motivation due to the manipulation in this group. *Time of measurement* served as within-subjects factor in each session. The VAS motivation values served as the dependent variable (see Table 1).

In session one, we found a significant main effect of motivation ($F(2, 28) = 5.56$, $p < .01$). While motivation did not increase significantly between t1 and t2 ($F(1, 16) = .12$, $p = .73$), post hoc contrasts revealed a significant increase between t2 and t3 ($F(1, 14) = 7.98$, $p < .05$). In sessions two and three, no main effect of motivation was found ($F(2, 28) = 1.82$, $p = .18$; $F(2, 28) = .17$, $p = .84$). Descriptively, VAS motivation was high ranging between 7.17 and 8.64 on average and increased from t1 to t3 in sessions 1 and 3 for the motivated group.

3.2 | Manipulation check emotion

As measured with the ADS-K, a mean value of $M = 10.65$ ($SD = 5.45$) was found when including the whole sample. No participant was clinically depressed.

TABLE 2 QCM-BCI means (*M*) and standard deviations (*SD*) for mastery confidence, incompetence fear, challenge and interest for the motivated group (Mo) and the unmotivated group (UM) in session 1

	Session 1					
	Mastery confidence			**Incompetence fear**		
	t1	**t2**	**t3**	**t1**	**t2**	**t3**
	M (SD)	***M (SD)***	***M (SD)***	***M (SD)***	***M (SD)***	***M (SD)***
Group						
Mo	5.87 (.81)	5.13 (1.29)	5.89 (.87)	2.21 (1.18)	2.04 (1.20)	2.01 (1.14)
UM	5.54 (.94)	5.43 (1.02)	5.24 (.79)	2.44 (1.09)	1.89 (.91)	2.07 (1.03)
	Interest			Challenge		
	t1	t2	t3	t1	t2	t3
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*
Group						
Mo	4.91 (.93)	4.83 (1.00)	5.41 (.98)	4.57 (.88)	4.53 (1.06)	5.02 (1.08)
UM	5.19 (.85)	4.92 (1.04)	4.74 (1.09)	4.81 (.98)	4.41 (1.16)	4.41 (1.26)

TABLE 3 QCM-BCI means (*M*) and standard deviations (*SD*) for mastery confidence, incompetence fear, challenge and interest for the motivated group (Mo) and the unmotivated group (UM) in session 2

	Session 2					
	Mastery confidence			**Incompetence fear**		
	t1	**t2**	**t3**	**t1**	**t2**	**t3**
	M (SD)	***M (SD)***	***M (SD)***	***M (SD)***	***M (SD)***	***M (SD)***
Group						
Mo	5.87 (.94)	5.67 (.95)	5.69 (.89)	1.82 (1.00)	1.80 (1.02)	1.93 (1.13)
UM	5.41 (.93)	5.37 (.96)	5.17 (1.37)	1.82 (.90)	1.78 (.95)	2.36 (1.36)
	Interest			Challenge		
	t1	t2	t3	t1	t2	t3
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*
Group						
Mo	5.14 (.92)	5.08 (.93)	5.13 (1.17)	4.52 (.74)	4.43 (.91)	4.54 (1.00)
UM	4.94 (.89)	4.99 (.93)	4.44 (1.11)	4.62 (.99)	4.36 (1.19)	4.30 (1.23)

To check for manipulation concerning emotional state, we used the SAM data in the participants who were manipulated for negative mood. A repeated measures ANOVA with *time of measurement* was calculated. SAM valence and arousal values served as the dependent variables.

In the first session, we found a main effect of valence ($F(2, 32) = 4.69$, $p < .05$). Post hoc contrasts revealed a significant decrease of values between t1 and t2 ($F(1, 16) = 9.77$, $p < .01$) and stable values between t2 and t3 ($F(1, 16) = .22$, $p = .65$). In the second session, we also found a main effect of valence ($F(2, 32) = 10.49$, $p < .001$). Post hoc contrasts revealed significantly more negative valence after as compared to before the manipulation of emotional state ($F(1, 16) = 10.32$, $p < .01$). No further changes occurred between t2 and t3 ($F(1, 16) = 2.24$, $p = .15$). In session three, no main effect of valence was found ($F(2, 32) = 1.96$, $p = .16$).

Concerning the SAM arousal values, we found a main effect of arousal in the first session ($F(2, 32) = 7.44$, $p < .01$). Post hoc analyses revealed no changes in arousal between t1 and t2 ($F(1, 16) = 1.84$, $p = .19$) but less arousal measured at t3 as compared to t2 ($F(1, 16) = 5.73$, $p < .05$). In sessions two ($F(2, 32) = .43$, $p = .65$) and three ($F(2, 32) = .67$, $p = .52$), no main effects of arousal were found.

Our manipulation was more successful in the first session and faded throughout further sessions. We found an increase in motivation in the first session, but contrary to our expectation, no increase in motivation in sessions two and three. We successfully elicited negative emotional state in the group who was manipulated to feel sad in the first

TABLE 4 QCM-BCI means (*M*) and standard deviations (*SD*) for mastery confidence, incompetence fear, challenge and interest for the motivated group (Mo) and the unmotivated group (UM) in session 3

	Session 3					
	Mastery confidence			**Incompetence fear**		
	t1	**t2**	**t3**	**t1**	**t2**	**t3**
	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**
Group						
Mo	5.60 (1.06)	5.62 (.97)	5.51 (1.05)	1.66 (.94)	1.66 (1.04)	1.67 (.99)
UM	5.34 (.99)	5.32 (1.02)	5.42 (.86)	2.05 (1.21)	1.88 (1.14)	1.94 (1.38)
	Interest			Challenge		
	t1	t2	t3	t1	t2	t3
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
Group						
Mo	5.22 (.96)	4.99 (1.11)	4.99 (1.18)	4.29 (1.08)	4.28 (1.05)	4.57 (1.06)
UM	4.91 (.84)	4.88 (.92)	4.72 (.95)	4.47 (1.26)	4.50 (1.20)	4.28 (1.15)

and second session. This effect was more pronounced in the SAM valence scale as compared to the SAM arousal scale.

3.3 | Description of motivated and unmotivated participants

The results of the motivation assessment via QCM-BCI are presented in Tables 2–4. We specifically focused on the last assessment of the day (t3) as in case motivation manipulation would influence subjectively reported motivation, this difference should maintain until the end of the training session. While descriptively, in session one at t3 all QCM-BCI subscale values indicated higher motivation in the motivated as compared to the unmotivated group (see Table 2), no statistically significant group differences were found.

In session two (see Table 3), again at t3 the QCM-BCI values were descriptively higher (lower for incompetence fear) in the motivated as compared to the unmotivated group. However, differences were not significant between the two groups.

In session three (see Table 4), all QCM-BCI subscale values were descriptively higher (incompetence fear lower) in the motivated as compared to the unmotivated group. No statistical difference between groups was found. Overall, no major changes in the subjective reporting of motivation as measured by the QCM-BCI subscales occurred, neither over time within one session (t1 to t3) nor across sessions (one to three).

In an exploratory analysis, we correlated the VAS motivation scale at t1 of every session with the according QCM-BCI subscale values to check which motivation component is most likely expressed in the VAS motivation. Due to violation of normal distribution criteria, we used Spearman's rho as correlation coefficient. We corrected for multiple correlations (Bonferroni) and adjusted the significance level to $\alpha = .0125$.

In the first session, VAS motivation correlated significantly with the QCM-BCI subscales interest ($r = .70$, $p < .001$) and challenge ($r = .57$, $p < .001$). In the second session, VAS motivation significantly correlated with mastery confidence ($r = .63$, $p < .001$) and interest ($r = .67$, $p < .001$) and marginally correlated with incompetence fear ($r = -.40$, $p < .05$). In the last session, a significant correlation with mastery confidence ($r = .43$, $p < .01$), interest ($r = .64$, $p < .001$) and challenge ($r = .44$, $p < .01$) was found. While we found a stable correlation between VAS motivation and the motivation component *interest*, other content-related overlap was inconsistent.

3.4 | Performance and *r*-squared s as a function of motivation (Hypothesis 1)

We hypothesized higher performance and *r*-squared values in participants who were motivated as compared to unmotivated participants. We calculated a repeated measures ANOVA with motivation as between-subjects factor, time of measurement as within-subjects factor, and performance as dependent variable. We found a significant main effect of time ($F(1.77, 58.39) = 3.30$, $p < .05$, see Figure 4). Descriptively, performance increased more constantly in the motivated as compared to the unmotivated group, which is also visible in the EEG activation (see Figure 5); however, we found no significant between group difference ($F(1, 33) = 2.08$, $p = .16$). Participants learned over time, but did so independent of group and, thus, Hypothesis 1a must be rejected.

Concerning the *r*-squared value, we calculated a repeated measures ANOVA with time of measurement (sessions one to three) as within-subjects variable, motivation as between-subjects variable and *r*-squared as dependent variable. We found a main effect of motivation ($F(1, 33) = 3.95$, $p = .017$, see Figure 6) with *r*-squared values being higher in the motivated group. As the distribution of the *r*-squared value did not fulfill the criteria for parametric testing in all sessions, we verified our results by using a nonparametric permutation-based ANOVA with $n = 1{,}000$ permutations. The significance level of the *F* value was confirmed ($p = .010$). To verify that this difference did not already exist during the calibration session, we calculated a Mann-Whitney *U* test which revealed a nonsignificant difference between the motivated and the unmotivated group during calibration ($U(1) = 148$, $p = .88$). Therefore, the *r*-squared difference occurred only after motivation manipulation. Hypothesis 1b was confirmed showing an effect of motivation on *r*-squared.

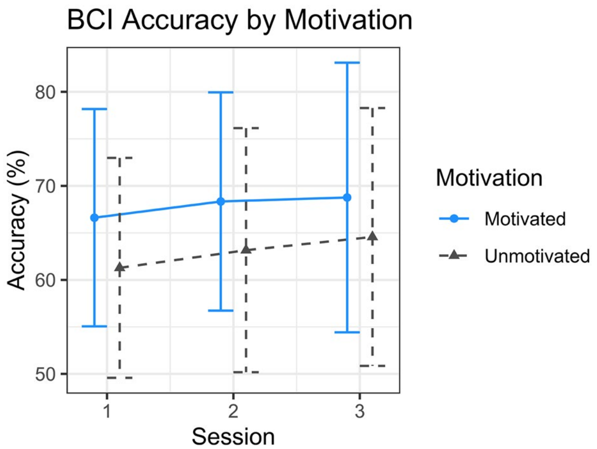


FIGURE 4 Performance in percent for the motivated and the unmotivated groups. Error bars indicated standard deviation

3.5 | Performance and *r*-squared values as a function of motivation and emotional state (Hypothesis 2)

We hypothesized higher performance and signed *r*-squared values in participants who were motivated and in neutral emotional state as compared to unmotivated participants in negative emotional state. We calculated a repeated measures ANOVA with group (motivated vs. unmotivated and neutral vs. negative emotional state) as between-subjects factor, and time of measurement as within-subjects factor; performance served as dependent variable. We found a marginally significant main effect of time ($F(1.89, 58.59) = 3.15$, $p = .05$, see Figure 7) but no main effect of group ($F(3, 31) = 1.06$, $p = .38$). On a descriptive level, the motivated group in negative emotional state performed best (see Figure 7) and the unmotivated group in neutral emotional state performed worst which is also visible in the EEG activation (see Figure 8). Thus, Hypothesis 2a was only partially confirmed. Motivation seemed to increase performance; however, emotional state did not have a strong effect on performance.

For evaluation of *r*-squared as a function of motivation and emotional state, we calculated a repeated measures ANOVA with group (motivated vs. unmotivated and neutral vs. negative emotional state) as between-subjects factor, time of measurement as within-subjects factor, and *r*-squared as dependent variable. We found a significant main effect of motivation ($F(1, 31) = 5.76$, $p = .02$, see Figure 9). No main effects of time ($F(2, 62) = 1.01$, $p = .37$,) or emotional state ($F(1, 31) = .028$, $p = .87$) were found, nor any further interaction. The hypothesized effect of motivation in combination with emotional state was not confirmed. Hypothesis 2b must be rejected.

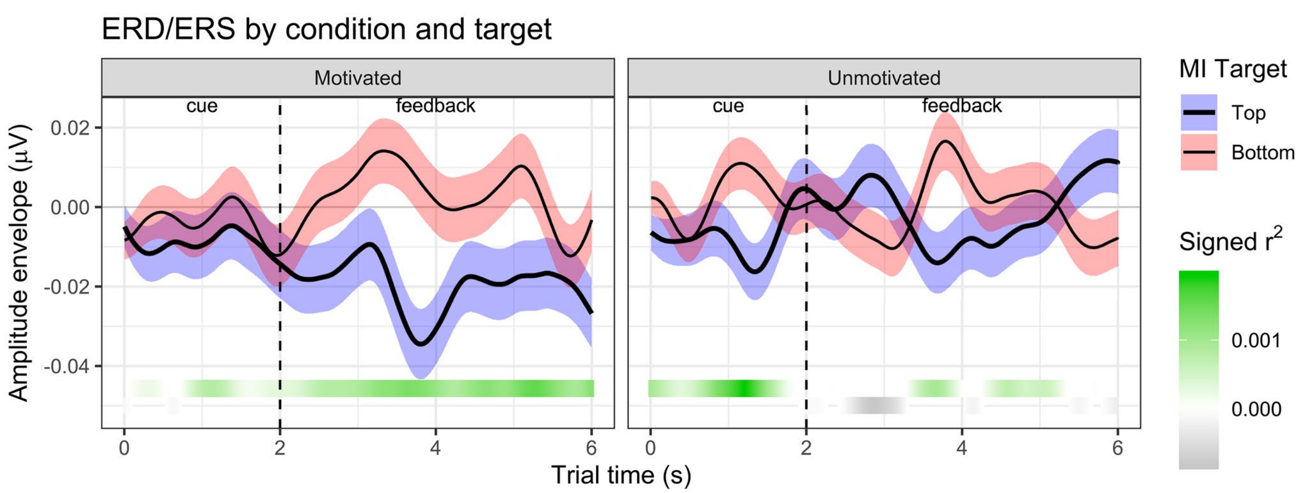


FIGURE 5 Grand average ERD/ERS amplitude as a function of time. Cue is provided at 0 s and feedback starts at 2 s. Thick line and blue color indicates target on the top, requiring an ERD while thin line and red color indicates bottom target, requiring an ERS. The *r*-squared values displayed on the bottom of the plots and their color indicate how congruent was the produced ERD/ERS with the cued target (green for congruent). Areas around lines represent standard error of the mean (*SEM*)

4 | DISCUSSION

In this study, our goal was to investigate the effect of extrinsic motivation manipulation via monetary reward and emotion manipulation via film clips and music on SMR-BCI performance. We found an effect of motivation but no unequivocal effect of emotional state.

4.1 | The effect of motivation on SMR-BCI control and motivation assessment

Motivation manipulation as well as emotional state manipulation was successful in the first session but seems to have faded over time within the session. Interestingly, motivation increased between t2 and t3 in session one and not between t1 (before manipulation) and t2 (after manipulation) contrary to our expectation. One explanation is that the pure information of having the opportunity to earn extra money did not increase motivation as compared to performing the BCI task and seeing the money bar increase on the screen. In this case, the paradigm itself would have been motivating which we intended by the design. The money bar display might have had by itself an effect on performance that was not only motivational. Carver and Scheier (1990) state that learners compare their performance to the goals they set beforehand and that this comparison does not only involve motivation but also influences the affective response, which in turn, might affect performance. High performance may be accompanied by negative affect as it might be possible to reach pre-set goals, but the cost of doing so may be high. In the present study, we showed, via the money bar, the participant his or her success in SMR-BCI control throughout the duration of the experiment and during all three sessions. In case a participant constantly envisaged the highest possible additional reward of 15€ but could not earn an extra 5€, the money bar feedback might have negatively influenced the emotional response as the pre-set goal was not met and could no longer be achieved in the remaining time of the experiment. Likewise, the participant may have been successful but had to focus intensively on the BCI task and, thus, experienced high cognitive load, which in turn also might have led to a negative emotional state. These effects might have interfered with our manipulation of the emotional state. However, due to our rather small group sizes, we cannot conclude such effects based on the here presented data and further research is needed for elucidation of such assumptions.

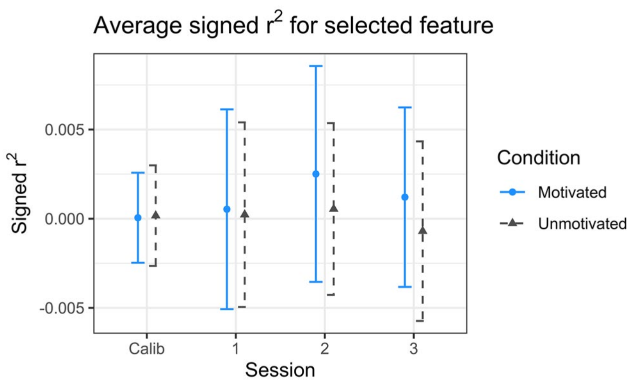


FIGURE 6 *r*-squared values for the motivated and the unmotivated groups for the calibration (calib) and all training sessions. Error bars indicate *SEM*

Furthermore, we used a standard feedback procedure for all participants. Adding an individually adapted feedback modality according to the preference of the user (e.g., auditory, tactile) might have increased involvement in the task and therefore task performance (Jeunet et al., 2018). Instead of using a monetary reward, incentives could be chosen individually (at the cost of giving up standardization) to increase motivation and thereby potentially boost self-regulatory capacity (Luciana & Collins, 2012).

Concerning motivation assessment, we used a visual analogue scale for the manipulation check and the QCM-BCI (Nijboer, Furdea, et al., 2008) for a description of the subsamples (motivated and unmotivated) comprising more detailed information on motivation components. While we initially found a significant difference in the VAS motivation

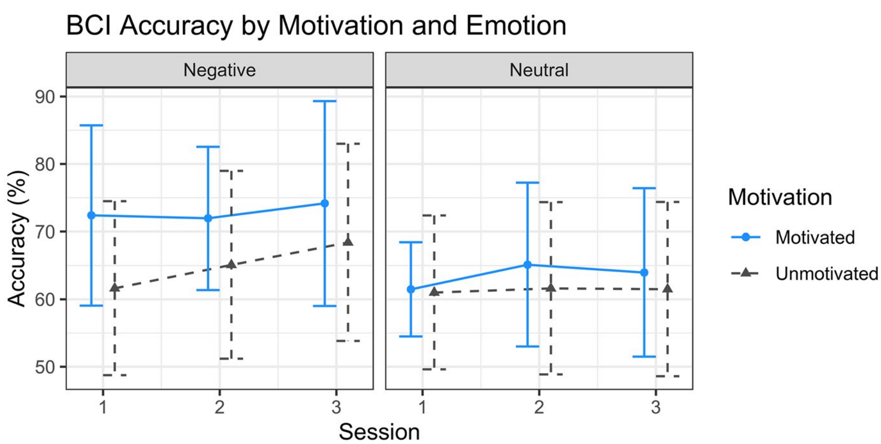


FIGURE 7 Performances in percentage of correct trials for sessions 1, 2, and 3 in the four groups motivated and unmotivated in negative emotional state and motivated and unmotivated in neutral emotional state. Error bars indicated standard deviation

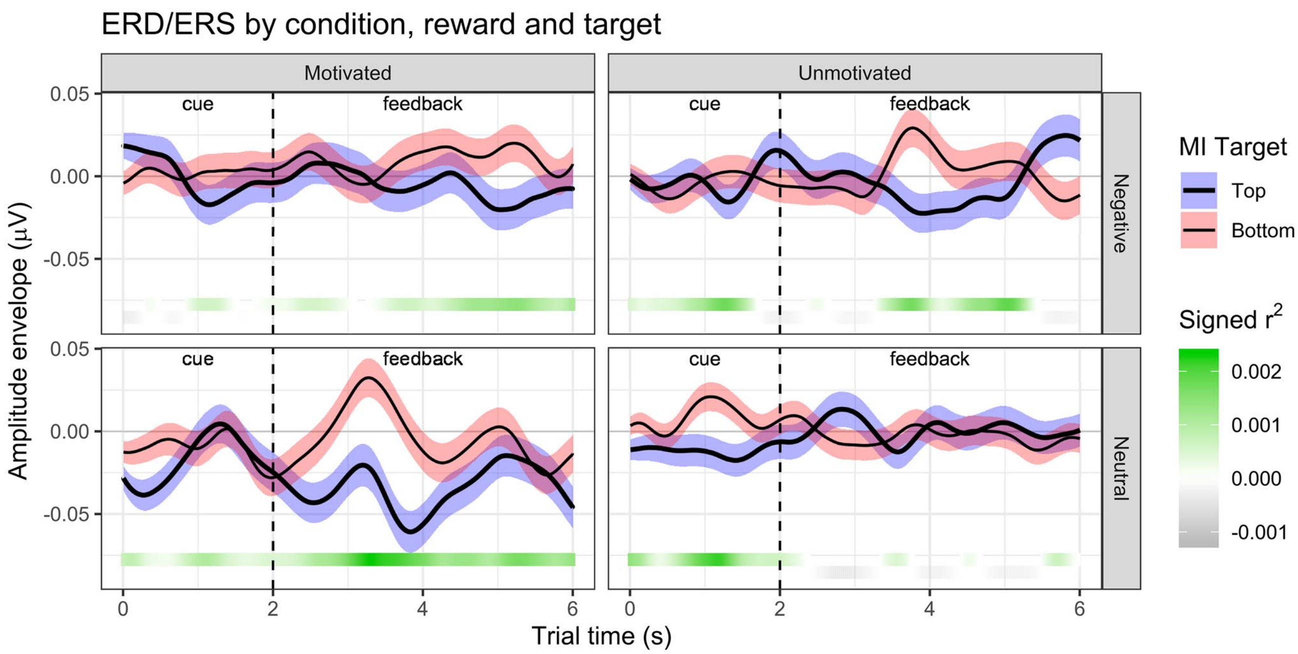
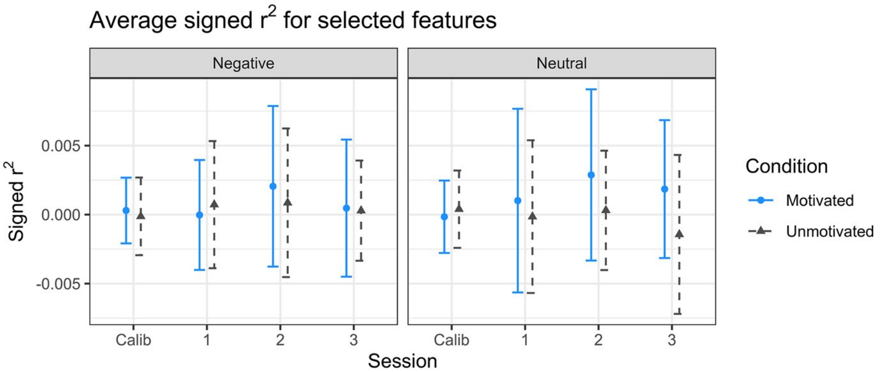


FIGURE 8 Grand average ERD/ERS amplitude as a function of time by motivation (motivated or unmotivated) and emotional state (negative or neutral). The cue is provided at 0 s and feedback starts at 2 s. Thick line and blue color indicates target on the top, requiring an ERD while thin line and red color indicates bottom target, requiring an ERS. The *r*-squared values displayed on the bottom of the plots and their sign indicate how congruent was the produced ERD/ERS with the cued target (green for congruent). Areas around lines represent *SEM*

FIGURE 9 *r*-squared activation for the calibration (calib), sessions 1, 2, and 3 in the four different groups motivated neutral, motivated negative, unmotivated neutral and unmotivated negative



when comparing the motivated and unmotivated subsamples, we could not find such difference in the QCM-BCI subscales. In an exploratory analysis, we found a significant correlation between the VAS motivation and the QCM-BCI subscale of interest in all sessions. However, all other QCM-BCI motivation components were not systematically correlated or uncorrelated to the VAS motivation. It seems that the VAS motivation partially assesses interest in the task but also other motivation components which seem less consistent over time. Interest is an important factor to be considered in a BCI context as interest in the BCI task per se might occur. It is possible that there are participants who are enthusiastic about BCI technology and research, and for them this interest is the actual reason for participation. During the process of participation in BCI research, the participant gets to know some facts and background about BCI technology and its use and interest might rise. This example describes Hidi's (2000) assumption of situational interest (BCI study participation because of reward) possibly turning into individual interest (wanting to know how BCI works; Ainley et al., 2002). Situational interest was defined as a result of conditions or objects that generate attention (Ainley, 1998; Hidi, 1990). Individual interest was defined as a relatively stable predisposition towards certain objects or activities (Ainley, 1998; Renninger, 2000). This situational to individual interest shift might be present in our data. Another possibility why the VAS motivation was correlated with the interest component might be found in the theoretical basis of the development of the original QCM by Rheinberg et al. (2001). They state that interest is a component which reveals objective interest in the task emphasizing voluntary task engagement while the other components mastery confidence, incompetence fear and challenge are performance oriented and therefore, much more dependent on the precise task requirements. Therefore, it might be deduced that the VAS motivation also assesses the least specific component which would be interest.

We found significantly higher *r*-squared values in motivated participants as compared to unmotivated participants; however, when comparing performances, this difference was not statistically significant. To calculate performance, the data were evaluated using the classifier that was determined as best suitable after the calibration session. However, the *r*-squared values were averaged for every participant and session for all trials performed. We did not readjust the classifier after every session as our goal was to investigate how motivation and emotional state influence learning. To facilitate learning by adaptation to the individual physiological state, the classifier could be adjusted after every training session in future studies. Retrospectively, our procedure was probably too rigid and might have hindered participants to unfold their potential for SMR-BCI control.

4.2 | The effect of emotional state on SMR-BCI performance

The induction of negative emotional state was successful as indicated by SAM valence but faded in the third session. Watching the same sad video clip for the third time might not have evoked the same negative emotional state as compared to the first and second time due to habituation processes (Hatta et al., 2006), and this noneffect could have possibly been prevented by using different stimuli for each session (Gross, 1998). Emotion induction may have been more stable in case participants could have chosen the music themselves (Cassidy & MacDonald, 2009). Cassidy and MacDonald (2009) found highest enjoyment, least arousal and highest efficiency in a computer driving game when participants could choose the music to listen to by themselves. According to Shih et al. (2009), the effect of music on performance depends on the personal taste. However, due to our highly standardized paradigm, we chose to disregard personal preferences. Even though sad and neutral emotion induction were shown to be possible (Martin, 1990), in our experiment, the effect of emotional state on SMR-BCI performance seems less clear as compared to the effect of motivation. While we hypothesized negative emotional state to have a detrimental effect on BCI performance, we found best performance in the motivated group in negative emotional state. As stated in Pekrun et al.'s (2006) model of achievement goals and emotions, motivation for learning and self-regulatory processes, such as needed for SMR-BCI control, might be mediated by emotional state. Positive emotions were hypothesized to positively influence motivation and to increase availability of cognitive resources for the learning task. Negative emotions were hypothesized to reduce cognitive resources and ability for self-regulated learning (Pekrun et al., 2006). However, negative emotions might also evoke motivation leading to the endeavor to provide extra cognitive resources to avoid failure (Pekrun et al., 2009). Or, as stated by Lazarus (1975), negative emotional state requires the one who experiences it to cope with denial or detachment as also observable in daily life situations. This effect also might occur anticipatorily (Lazarus, 1975) which might explain the vanishing effect of our manipulation over sessions. Participants anticipated their negative emotions already before the session and possibly denied unconsciously perception. Jefferies et al. (2008) state that people in a sad emotional state focus more on the details but not so much on the content, which might be applicable here as contextual information to be processed did not change. Negative emotion would prevent distracting stimuli to be processed and focus cognitive capacities on the target task. However, if this was the case, also participants with negative emotion in the unmotivated state should have presented with higher *r*-squared values as compared to participant groups in neutral emotional state which was not the case.

4.3 | Limitations of the study

In this study, we evaluated data of 35 participants who were trained on three days within one week and were assigned to four groups, which led to a low sample size per group. Further, the number of training sessions was low. The lack of a state of positive emotion could also be criticized. However, all these aspects would have increased the already high number of 105 training sessions. Concerning the EMG electrodes, we used electrodes assessing the activity of muscles that are usually needed for larger movements of the wrist and arm. Using electrodes at the locations assessing activation of the finger of the flexor digitorum superficialis and activation of the leg from the lateral malleolus of the fibula could have been added to control for unconscious muscle activation from imagination of smaller movements.

The effect of motivation and emotional state manipulation faded over time. We used additional monetary reward as suggested already by Peper and Mulholland (1970). One could argue that our monetary reward was small with 5 Cents per trial or a total of 5 € per session, but it could increase to 15€ altogether. In this study, we only focused on extrinsic motivation (Ryan & Deci, 2000) as manipulated by monetary reward. However, intrinsic motivation and promoting its occurrence (Kleih & Kübler, 2013) might be a useful and efficient further step toward elucidating the effect of motivation on BCI performance.

4.4 | Conclusion

The here presented study was set up such that causal inference would have been possible. As we found that performance improved over time and that the motivated group outperformed the unmotivated group, we can attribute this effect on our incentive of monetary reward. We found, as previous research, an effect of motivation on BCI performance (Hammer et al., 2012, 2014; Jeunet et al., 2016). The exact nature of this effect needs to be further clarified by future research as interactions of psychological processes affecting BCI performance are still unknown, however hypotheses on psychological processes influencing BCI performance were already investigated. Myrden and Chau (2015) for example found an effect of frustration on BCI performance. As frustration often is closely linked to performance, it is an emotional state that might play a role in many BCI experiments. As Jeunet and colleagues summarized (2017), potential factors influencing SMR-BCI performance such as attention, motivation and engagement toward the task should be disentangled and investigated in thoroughly designed experiments to allow for strong inference.

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CONFLICT OF INTEREST

We hereby declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

Sonja Christina Kleih-Dahms: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Visualization; Writing-original draft. **Loic Botrel:** Formal analysis; Visualization; Writing-review & editing. **Andrea Kübler:** Methodology; Resources; Supervision; Validation; Writing-review & editing.

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