Emotion

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Smiling and Frowning Induced by Facial Neuromuscular Electrical Stimulation (fNMES) Modulate Felt Emotion and Physiology

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According to the facial feedback hypothesis, feedback from facial muscles can initiate and modulate a person's emotional state. This assumption is debated, however, and existing research has arguably suffered from a lack of control over which facial muscles are activated, when, to what degree, and for how long. To overcome these limitations, we carried out a preregistered experiment including 58 participants. Facial neuromuscular electrical stimulation (fNMES) was applied to the bilateral zygomaticus major and depressor anguli oris muscles for 5 s at 100% and 50% of the participants' individual motor threshold. After each trial, participants reported their emotional valence and intensity and levels of experienced discomfort. Facial muscle activations were verified with automatic video coding; heart rate and electrodermal activity were recorded throughout. Results showed that muscle activation through fNMES, even when controlling for fNMES-induced discomfort, modulated participants' emotional state as expected, with more positive emotions reported after stronger stimulation of the zygomaticus major than the depressor anguli oris muscle. The addition of expression-congruent emotional images increased the effect. Moreover, fNMES intensity predicted intensity ratings, reduced HR, and skin conductance response. The finding that changes in felt emotion can be induced through brief and controlled activation of specific facial muscles is in line with the facial feedback hypothesis and offers exciting opportunities for translational intervention.

Keywords: facial neuromuscular electrical stimulation, facial muscles, emotion, facial feedback, electrical stimulation

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The facial feedback hypothesis (FFH) posits that facial expressions not only reflect emotions but can also actively shape them, as the brain receives proprioceptive feedback about changes in facial muscle activation (Adelmann & Zajonc, 1989; Laird, 1974; McIntosh, 1996; Strack et al., 1988). For instance, smiling can initiate or amplify feelings of happiness, while frowning has been linked to heightened negative affect (Coles et al., 2022; Davey et al., 2013; Flack, 2006). Inhibiting facial muscle movement, on the other hand, weakens the experience of the corresponding emotion (Davis et al., 2009). These findings have highlighted the bidirectional relationship between facial expressions and emotional experience (Coles et al., 2019).

Facial feedback effects can also modulate the activity of the autonomic nervous system. For instance, actors portraying anger, fear, and sadness displayed elevated heart rates (HRs)—a measure

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of beats per minute that typically rises with emotional arousal and stress (Kreibig, 2010; Levenson, 2014)—compared to those depicting happiness, surprise, and disgust (Ekman et al., 1983). Further, smiling reduces stress, with individuals smiling unconsciously showing lower HR during recovery from a stressful task and smaller decreases in positive affect from baseline (Ansfield, 2007; Kraft & Pressman, 2012). Similarly, Duchenne compared to non-Duchenne smiles result in higher electrodermal activity (EDA), which measures the skin's conductivity and varies with emotional arousal (Kreibig, 2010), and HR when exposed to positive stimuli (Soussignan, 2002). Disrupting facial feedback, on the other hand, can diminish physiological responses. Indeed, Parkinson's patients, who have reduced facial mimicry and emotion recognition (Argaud et al., 2018; Kuehne et al., 2023), also show lower EDA to negative and highly arousing images (Balconi et al., 2016).

The FFH is controversial, however, as facial feedback effects are small and variable (Coles et al., 2019), as they are, for example, influenced by demand characteristics (Coles et al., 2023), social context (Phaf & Rotteveel, 2023), and stimulus choice (Marmolejo-Ramos et al., 2020). Furthermore, influential findings are not always replicated. For example, a multilab study (Wagenmakers et al., 2016; but see Noah et al., 2018) failed to replicate the seminal finding that holding a pen between the teeth, thereby mimicking a smile, increases feelings of amusement toward cartoons (Strack et al., 1988). The inconsistency in the literature may be the result, at least partly, of limitations of the methods used to activate or inhibit facial muscles.

Various experimental methods have so far been used to manipulate facial muscle activity and study facial feedback effects. Common approaches include asking participants to voluntarily pose a facial expression (Laird, 1974) or inducing facial muscle activation indirectly, such as through the pen-in-mouth technique, where muscles linked to smiling or frowning are activated or inhibited by holding a pen between the teeth or lips, respectively (Sel et al., 2015; Wingenbach et al., 2018). Studies have also looked at emotion and emotion perception in individuals with congenital or acquired facial paralysis (Korb et al., 2016; Schiano Lomoriello et al., 2024), including those induced by Botox injections (Davis et al., 2010). Facial muscle activity and facial feedback have also been manipulated by placing tape (Carpenter & Niedenthal, 2020) or hardening gels (Neal & Chartrand, 2011; Wood et al., 2016) on the facial skin.

The methods used, so far, to activate or inhibit facial muscles suffer from certain limitations, which might explain the weakness and inconsistencies of findings. For example, while the pen-in-mouth method offers the advantage of not requiring explicit references to emotions or emotional expressions, it does not allow to precisely control which facial muscles are activated to what degree (or even symmetry) and for what duration. In addition, voluntary posing of facial expressions is effortful, and not all participants can adequately engage the necessary muscles (Coles et al., 2022). Botox injections are an invasive procedure whose effects last for several months, making them less than ideal for controlled laboratory settings, where researchers are typically interested in the immediate effects of generating or blocking an expression. Similarly, long-lasting facial paralysis likely results in compensatory mechanisms. Therefore, a major aim of this study was to provide a more controlled test of the FFH using a method that allows to target specific muscle groups with precise intensity and timing. Moreover, we aimed to measure the effects of muscle stimulation on peripheral physiology, in addition to subjective ratings.

To accurately activate specific facial muscles, the present study used facial neuromuscular electrical stimulation (fNMES). It consists of delivering electrical currents to facial muscles using surface electrodes, allowing researchers to activate specific facial muscles noninvasively and with high temporal precision. We recently published a review of the literature on human surface fNMES and provided recommendations on how to implement it in the psychology laboratory and combine it with EEG (see Baker et al., 2023; Efthimiou, Baker, et al., 2024; Efthimiou, Hernandez, et al., 2024). fNMES has great potential for testing aspects of the FFH However, to date, only a handful of studies have employed fNMES within the framework of the FFH. Yen-Chin et al. (2017) reported that eight participants felt aided in smiling and increased amusement when fNMES was applied to their zygomaticus major (ZM) and orbicularis oculi (OO) muscles. Zariffa et al. (2014) found that 12 participants who received fNMES to bilateral ZM and OO muscles while voluntary smiling reported reduced fear and increased determination, compared to 12 participants who smiled voluntarily but did not receive fNMES. Kapadia et al. (2019) reported symptom improvement in 10 individuals with major depression following 10–40 sessions of fNMES to ZM and OO, though their design did not include a control group. Warren (2021) found that, when weak fNMES is applied to the ZM muscle, which is responsible for lifting the corners of the mouth during a smile—an action linked with positive emotions (Ekman & Friesen, 1978; Soussignan, 2002)—individuals experienced enhanced positive feelings when looking at positive images. This highlights the potential for fNMES to be used as a tool to modulate emotional responses. Finally, we recently demonstrated that very short and weak bilateral smiles, induced by fNMES, can lead to an increase in the perception of happiness in ambiguous facial expressions (Efthimiou, Baker, et al., 2024). These results are promising but should be considered preliminary, given that small sample sizes were often employed and that in several studies fNMES was delivered in conjunction with voluntary posed smiling (not allowing for isolating the fNMES effects). Further, the measure of emotional state was not taken immediately after fNMES delivery, but rather after a 25-min session. This is problematic because facial feedback effects are known to dissipate after about 4 min (Söderkvist et al., 2018; Experiment 1).

To address the gaps in the literature and delve deeper into the potential of fNMES as a tool for investigating facial feedback effects, our preregistered study (Efthimiou et al., 2023) aimed to accomplish four objectives. First, we wanted to examine if fNMES-induced expressions alone are enough to produce facial feedback effects, as prior research often combined fNMES with posed expressions (Kapadia et al., 2019; Zariffa et al., 2014). Second, we wanted to explore whether fNMES is capable of both initiating emotion in the absence of a visual stimulus and modulating emotional states generated by a visual stimulus (Coles et al., 2019). Third, we wanted to study the effects of fNMES on muscles associated with negative emotions, as previous work only studied smiles. We, therefore, targeted the depressor anguli oris (DAO) muscle, which is part of the typical sadness expression (Ekman et al., 2002; Reisenzein et al., 2013), to investigate if its activation through fNMES can induce or amplify feelings of sadness. While the corrugator muscle is a common choice for studies of sadness (Arias et al., 2020), we opted for the DAO and ZM muscles due to their location in the lower face, where similar fat content can lead to analogous sensations regardless of the targeted muscle. This makes

for a better comparison in evaluating the effects of emotional expressions and allows us to specifically examine the unique emotional effects associated with the activation of sadness-related facial expressions. Fourth, we varied the intensity of fNMES. Previous work suggested that facial feedback effects can be induced by both weak, nearly imperceptible fNMES (Warren, 2021) and by higher fNMES intensities that elicit visible muscle contractions (Kapadia et al., 2019; Zariffa et al., 2014). The effects of both weak and stronger fNMES on emotion have, however, not yet been tested together in the same study.

To this end, our study employed fNMES to discern changes in participants' subjective emotional experiences as measured by self-report and peripheral physiology. Facial muscles associated with happiness (ZM) and sadness (DAO) were bilaterally stimulated for 5 s at three fNMES intensity levels: (a) 100% of each individual's motor threshold (MT), corresponding to the minimum intensity to reliably see weak muscle activation; (b) 50% of MT, which induces cutaneous tingling but no observable movement; and (c) 0% of motor threshold or "off," as no stimulation was delivered. For statistical analyses, the two muscles and three intensities were combined into a single continuous variable with five levels (DAO 100%, DAO 50%, off, ZM 50%, and ZM 100%), hereinafter called fNMES. To strengthen the fNMES effect, positive, negative, or neutral images were also shown in some trials.

We predicted (Hypothesis 1) that systematically varying fNMES intensity, from stimulation targeting sadness (DAO 100%) through to stimulation targeting happiness (ZM 100%), will result in progressively more positive valence ratings. This pattern suggests that facial muscle activation, specifically shifting from sadness-related muscles to happiness-related muscles, influences the emotional state toward greater positivity. Moreover, (Hypothesis 2) we anticipated that the effect observed in Hypothesis 1 (greater valence with increasing levels of fNMES) would be more pronounced when participants view emotion-congruent images compared to neutral images or when no image is present. We expected a higher HR (Hypothesis 3) and skin conductance response (SCR, Hypothesis 4) at higher fNMES intensities, reflecting a startle response. Moreover, because either only the ZM or the DAO muscles were targeted in each block and the repeated activation of the same muscle over the duration of a block could modulate mood, we expected the ZM block to result in greater HR (Hypothesis 5) and higher skin conductance level (SCL, Hypothesis 6), relative to the block with DAO muscle stimulation.

Method

Research Design

The study used a within-subjects experimental design. Participants received fNMES to the ZM and DAO muscles in the same session but in separate blocks—each block consisted of 36 trials and lasted 20–30 min. The muscle order was counterbalanced across participants.

Participants

To determine the appropriate sample size, an a priori power analysis was conducted based on data from Coles et al. (2023), which used a similar design. Our study differs in how we manipulated facial expressions and which expressions were generated. Specifically, Coles et al. (2023) asked participants to voluntarily pose happy and angry faces, while we used fNMES to induce expressions of both happiness and sadness. Due to these methodological differences, we reduced our anticipated effect size to $\beta = 0.10$. To facilitate cross-study comparison, the rating of self-reported happiness from Coles et al. (2023) was transformed into a 100-point scale, and facial expressions were converted into numeric variables. These transformed data were standardized and analyzed using the lme4 package (Bates et al., 2015) in R (formula: rating ~ fNMES + (1 | participants)). Subsequently, a power analysis was conducted using the MixedPower package (Kumle et al., 2021), enabling us to simulate a linear mixed-effects model (LMM) that accounted for trial and sample-size variations. Based on 1,000 simulations with four trials per condition, a sample size of 45 was estimated to provide 92% power for the detection of a main effect of fNMES when no image was present.

Expecting some data loss, we tested 60 participants, of which one was excluded due to experimenter error and another because no reliable ZM activation could be generated. For the analysis of physiological data, another 10 participants were excluded due to low-quality data (see description of data cleaning in the Data Preparation and Analyses section). Final sample sizes were thus 58 for ratings (female = 38; $M_{age} = 24.57$, $SD_{age} = 5.54$) and 48 for physiology (female = 31; $M_{age} = 23.85$, $SD_{age} = 5.01$). The study was approved by the University of Essex ethics committee (ETH1920-0847) and carried out in 2023. All participants provided informed consent.

Equipment and NMES Parameters

The delivery of fNMES was achieved using two DS5 constant current electrical stimulators (Digitimer, Welwyn, United Kingdom) and in-house built digital-to-analogue converters. Stimulation was administered using a 70-Hz train of biphasic square pulses with a width of 100 μs and a pulse delay of 14 ms. We used disposable Ag/AgCl electrodes measuring 16 × 19 mm (Ambu BlueSensor BRS, surface area = 3.04 cm^2). The maximum stimulation intensity was 35 mA, which corresponds to 0.96 root-mean-square mA/cm^2, and is well below the advised safety threshold of root-mean-square 2 mA/cm^2 and follows the safety guidelines outlined in EN 60601-2-10: 2000 (see Efthimiou, Hernandez, et al., 2024).

For measures of skin conductance, two disposable 24-mm Ag/AgCl pregelled electrodes (Kendall H124SG model) were placed around the middle and index finger of the nondominant hand, while a disposable electrode placed on the wrist of the same hand served as a system ground. To measure HR, a photoplethysmogram sensor was placed on the index finger of the nondominant hand. Both EDA and HR data were amplified using an ANT eego sports amplifier and were recorded throughout the entire testing session at 512 Hz.

Procedure

Before the laboratory session, participants completed a Qualtrics survey assessing alexithymia—that is, difficulties in identifying and describing feelings—using the Toronto Alexithymia Scale (TAS; Taylor et al., 1985). Additionally, participants reported any prior

experience with electrical stimulation applied to the body or face. To address concerns regarding the application of fNMES, participants rated their excitement and worry about receiving facial NMES on two Visual Analogue Scales (VAS). They indicated their agreement with the statements "I am excited about receiving facial NMES" and "I am worried about receiving facial NMES" using a scale from 0 = *strongly disagree* to 100 = *strongly agree*. This assessment was informed by the findings of Efthimiou et al. (2022), who highlighted participants' concerns regarding the risks associated with fNMES. Both alexithymia and concern with fNMES were controlled for by including them as covariates.

Upon arriving at the laboratory, participants were given a detailed description of fNMES (see Supplemental S1), specifying its prior use in facial paralysis research and emphasizing the safety of the technique. To avoid drawing immediate attention to the concepts of emotion and mood, a cover story was used: Participants were informed that the experiment investigated the comfort of various fNMES intensities. Participants were seated in a sound-attenuated booth positioned 60 cm from the center of a 24.5-in. screen (Alienware aw2521h) with a resolution of 1920 × 1,080 pixels and a refresh rate of 360 Hz. To verify correct muscle activation patterns, participants' faces were recorded using a Logitech webcam, sampling at 15 frames per second.

At the start of each block, the experimenter cleaned the participants' cheeks and chin area using alcohol wipes (70% isopropyl alcohol) before placing fNMES electrodes. Only one bilateral muscle was targeted in each block, placing two electrodes per muscle following electromyography guidelines (for a visual aid, see Efthimiou, Hernandez, et al., 2024; Fridlund & Cacioppo, 1986). Thus, electrodes were placed on the left and right ZM muscle in one block and on the left and right DAO muscle in the other block. Optimal electrode positions and stimulation intensity were established in a calibration phase at the beginning of each block. Specifically, 500 ms of fNMES were administered starting at 5 mA and gradually increasing in increments of 5 mA, until inducing visible contraction of the muscle of interest (the corresponding intensity defined as the participant's individual MT). During the stimulation period, the participant's face was visually inspected for noticeable muscle contractions according to the respective muscle function. For example, when stimulating the ZM, the lip corner moves up and toward the ears, whereas stimulation of the DAO makes the lip corner move down toward the chin. If the muscle contractions were not satisfactory or participants reported high levels of discomfort, electrode positions were changed slightly. This process was repeated until the administrator considered the contractions to be adequate. Once a comfortable and optimal electrode placement and intensity were found, fNMES was delivered for 5 s three times to introduce the subjects to the parameters defined in the experiment.

The experiment was programed in PsychoPy v2021.1.4 (Peirce et al., 2019). To obtain a baseline of EDA and HR activity, participants began by sitting still and watching a video of a moving ball for 3 min. To assess mood, we employed two distinct measures. First, we utilized a VAS with anchors ranging from 0 = *low mood (sad/angry)* to 100 = *high mood (happy/cheerful)* to measure baseline mood at two time points: (a) at the beginning of the first experimental block and (b) at the start of the second block. This allowed us to compare mood changes within the session. Second, we administered the Positive and Negative Affect Schedule (Watson et al., 1988) only once at the very beginning of the experiment. This score served as a covariate to account for preexisting mood differences between participants.

Thereafter, the first block of fNMES began, comprising 36 trials presented in a pseudorandom order (avoiding back-to-back repetitions of the same fNMES intensity). In the first 12 trials, participants received 5 s of fNMES at 0%, 50%, or 100% of MT while viewing a fixation cross at the center of the screen (no-image condition). In the remaining 24 trials, a neutral or stimulation-congruent image was shown in conjunction with fNMES. Images were selected from the Open Affective Standardized Image Set from three categories: objects, animals, and scenes (Kurdi et al., 2017; see Supplemental Table S2 for the list of images selected). Both blocks included neutral and no-image conditions. However, the ZM block only had positive and neutral images, while the DAO block only had negative and neutral images. After each trial, participants were shown three 100-point VAS through which they reported the valence and the intensity of their emotions and the amount of fNMES-induced discomfort. Valence was measured with the item "Rate how you feel right now" and had anchors from 0 = *negative/low* to 100 = *positive/high*. Intensity was measured with the item "Rate the intensity of your feelings," with anchors from 0 = *not at all intense* to 100 = *extremely intense*. fNMES-induced discomfort was measured by asking "How uncomfortable did you find the stimulation?" and had anchors from 0 = *not at all uncomfortable* to 100 = *extremely uncomfortable*. At the end of each block, participants were asked "Please rate to what extent the stimulation felt like you were: smiling/frowning," for which they used two 100-point VAS with anchors 0 = *not at all* and 100 = *very much* (Figure 1).

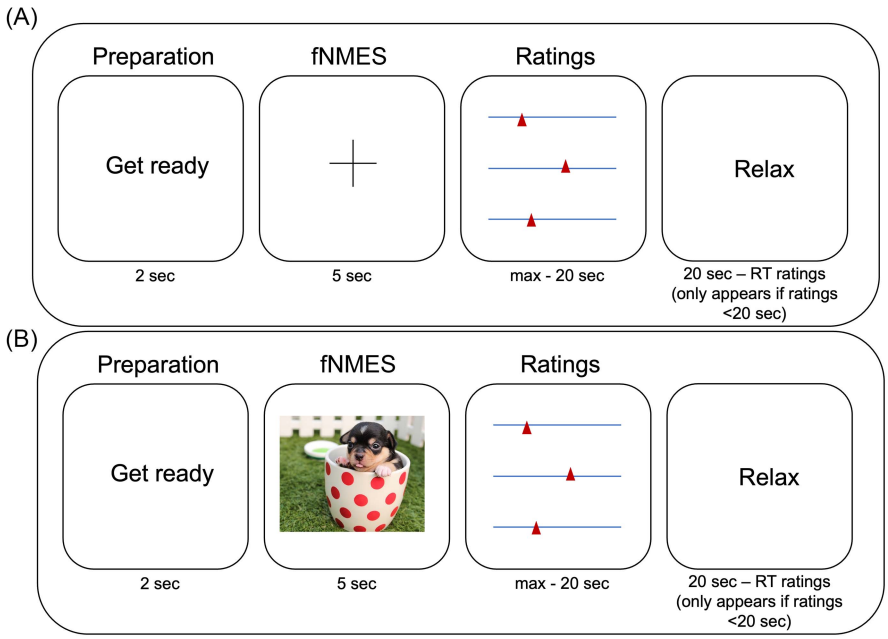
Data Preparation and Analyses

Behavioral data processing and statistical analyses were performed using R (R Core Team, 2020). Self-reported valence, intensity, discomfort, positive and negative affect, and alexithymia were *z*-score transformed. Further, fNMES was organized based on muscle and fNMES intensity,[1] resulting in the order: DAO 100%, DAO 50%, off, ZM 50%, ZM 100%, and converted into numerical values ranging from −2 to 2. The visual stimuli were also categorized into three groups: no image, neutral, and congruent. Congruent stimuli are those in which the participant's facial expression matches the emotional content of the visual stimulus. For example, a negative image is considered congruent in trials with fNMES applied to the DAO.

In total, 2.98% of all trials were excluded from the analysis for the following reasons. First, we excluded trials in which participants failed to rate intensity and discomfort within the provided 20 s (0.17% of all trials). Second, we noticed that in some cases participants reported high levels of discomfort related to fNMES in situations where fNMES was not administered (off condition), suggesting a random or erroneous response. Therefore, we excluded any trials in the fNMES off condition, where the reported discomfort exceeded twice the standard deviation of the mean (i.e., discomfort ≥ 35; 82 trials, 2% of all trials). Finally, we rejected trials with valence,

[1] This corresponds to the preregistered analysis. However, we also provide results for the analysis, keeping muscle and fNMES intensity separate (see Supplemental S4).

Figure 1
Example of Two Trials



Note. During a single trial, participants were given a 2-s warning before receiving fNMES at varying intensities, either at 0% (off), 50%, or 100% of MT. The experiment consisted of two blocks of 36 trials. (A) illustrates the first 12 trials presenting a fixation cross only. (B) illustrates the subsequent 24 trials in which an image from the Open Affective Standardized Image Set database was shown. At the end of each trial, participants rated the valence and intensity of their felt emotion, as well as felt discomfort. The trial ended when all three questions had been completed or after the 20 s elapsed, whichever occurred first. A rest period was then provided, which lasted for 20 s minus the time taken to respond. fNMES = facial neuromuscular electrical stimulation; MT = motor threshold; RT = reaction time. The image used in this Figure (a dog in a teacup) was obtained from the Open Affective Standardized Image Set (OASIS), which is an open-access database. The OASIS images can be freely reused and modified for research and publication, as detailed in Kurdi et al. (2017). See the online article for the color version of this figure.

intensity, or discomfort ratings ±3.29 *SD* (33 trials, 0.81% of all trials) as they were considered outliers.[2]

LMMs were conducted using the lme4 package (Bates et al., 2015), and *p* values for fixed effects in LMMs were computed using the lmerTest package (Kuznetsova et al., 2017). To analyze main and interaction effects, the emmeans package (Lenth, 2023) was utilized, from which we report estimated marginal means. Model comparisons were conducted using the analysis of variance function. To evaluate model performance and test its accuracy, we used the performance package (Lüdecke et al., 2021) to extract conditional R^2 and marginal R^2 values. The confint function was employed to extract 95% confidence intervals.

To verify that fNMES delivery resulted in the intended muscle activation, the video recordings of each participant were segmented into 7-s clips (−1 s to 6 s post-fNMES onset), and facial muscle activity was coded based on the Facial Action Coding System (Friesen & Ekman, 1978) using the OpenFace toolkit (Baltrusaitis et al., 2018). The software provides a confidence rating (0–1) for each frame, which indicates the tracker's confidence in the detection of activity in an action unit (AU). These confidence ratings were averaged across all frames for a single trial, and we rejected trials in which confidence was <95%. The data were baseline corrected by subtracting the average of the preceding −500 ms from each subsequent time point. We extracted activation levels for AU12 (corresponding to the ZM) and AU15 (corresponding to the DAO) as our primary index of smiling and frowning, respectively. Further, we extracted activation of two related but nontarget AUs, specifically AU6, which corresponds to the OO muscle and is engaged during a Duchenne smile (Ekman et al., 1990), and AU4, which is a measure of corrugator supercilli activity resulting in the lowering of the brow. This was done to confirm that fNMES did not recruit other surrounding muscles. Further, AU4 was to ensure that participants were not grimacing due to discomfort (Pressman et al., 2021).

Physiological data were processed using MATLAB and the EEGLAB toolbox (Delorme & Makeig, 2004). Skin conductance was analyzed in two ways. For block-level (tonic) responses (SCL), data were detrended (removal of the mean across all samples) and then subjected to a 10-Hz low-pass filter. Mean activity in the baseline periods (2-min video that preceded each stimulation block) was calculated and subtracted from the respective mean activity during each stimulation block (i.e., DAO and ZM separately), resulting in baseline-corrected tonic activity during the application

[2] Inclusion of these trials does not change the pattern of results.

of successive stimulations to DAO and ZM. For event-related activations (i.e., phasic SCR), a 0.1-Hz high-pass filter was applied before data were segmented into 21-s epochs (1 s before the onset of the stimulation and 20 s following the stimulation). Epochs were baseline-corrected by removing the mean activity of prestimulation activations. The amplitude of SCR was quantified for each trial by taking the mean of the samples between 2 s and 10 s after the onset of stimulation. The first 2 s of data were discarded because the changes in the data were too fast to be a SCR (Ohira & Hirao, 2015). The next 8 s were used based on a visual inspection of the data.

For HR measures, the findpeaks function in MATLAB was used, with the minimum peak distance parameter set to 300. We confirmed this through a visual inspection for 1 min, confirming the correct number of peaks were counted. This demonstrated that this was sufficient to extract the number of peaks in the photoplethysmogram signal. For the block-level analysis, similarly to the SCL analysis, HR (in beats per minute) was calculated in each baseline period and subtracted from the HR observed during each stimulation block. This resulted in an HR change measure for each block, which allowed us to examine whether HR increased or decreased during each block, relative to the baseline. HR was also derived in the event-related analysis, whereby the number of peaks in the photoplethysmogram signal was derived in each trial.

Transparency and Openness

We have provided a full account of our sample size determination, justifications for data exclusion, and comprehensive descriptions of all measures used within our research. The materials supporting our research, analysis script, and preregistration are openly accessible through the Open Science Framework (Efthimiou et al., 2023).

Results

Participants reported a moderate level of excitement ($M = 63.02$, $SD = 25.38$) and a low level of worry ($M = 23.64$, $SD = 25.56$) at the prospect of receiving fNMES. Only five participants reported prior experience with some form of electrical stimulation; two were for medical and three for research purposes. All five were retained for further analyses. Alexithymia scores were low in 34 participants (TAS score ≤ 50), medium in 11 (TAS score 52–60), and high in another 11 participants (TAS score ≥ 61).[3] TAS scores were missing for two participants. A linear regression revealed an interaction between muscle stimulated (ZM or DAO) and ratings of expressions, smile or frown; $R^2 = .55$, $F(3, 228) = 98.1$. In the DAO block, participants reported feeling that fNMES induced more frowning ($M = 77.04$, $SD = 25.35$) than smiling ($M = 16.91$, $SD = 26.05$). Conversely, in the ZM block, participants felt that fNMES made them smile ($M = 70.21$, $SD = 26.97$) more than frown ($M = 21.33$, $SD = 24.16$).

We performed a linear regression to examine fNMES amplitude by muscle and side of the face, $R^2 = .03$, $F(3, 228) = 2.02$. A main effect of muscle emerged, indicating that the DAO muscle required a higher current to contract than the ZM, $\beta = 33.36$, 95% CI [1.97, 64.75], $t(228) = 2.09$, $p = .037$. Current intensity did not differ between the left and right hemi-face, $\beta = 2.50$, 95% CI [−28.89, 33.89], $t(228) = 0.16$, $p = .875$. Finally, no interaction between muscle and side emerged, $\beta = -13.79$, 95% CI [−58.19, 30.60], $t(228) = -0.61$, $p = .541$. Thereafter, the currents for each side of the face were averaged for statistics. The mean fNMES intensity applied was 22.96 mA ($SD = 4.25$, range = 15.38–33.75) for the DAO and 24.29 mA ($SD = 3.98$, range = 15.25–35) for the ZM.

Activation and relaxation patterns across four AUs (4, 6, 12, 15) were extracted automatically from video recordings using automatic Facial Action Coding System coding. This allowed us to observe (Figure 2) DAO activation (AU15) and ZM relaxation (AU12), when fNMES was delivered at 100% of MT to the DAO muscle. The opposite pattern of DAO relaxation and ZM activation, as well as some OO activation (AU6), was found when the ZM muscle was targeted with fNMES. The activity of the corrugator supercilli muscle (AU4) was low and similar across fNMES targets. Importantly, no substantial changes across all four AUs occurred when fNMES was delivered at 50% of MT or when fNMES was off. To summarize, the intended target muscles DAO and ZM were reliably activated with fNMES at 100% MT, while they stayed at baseline level when lower intensity fNMES or no fNMES at all were applied.

Ratings

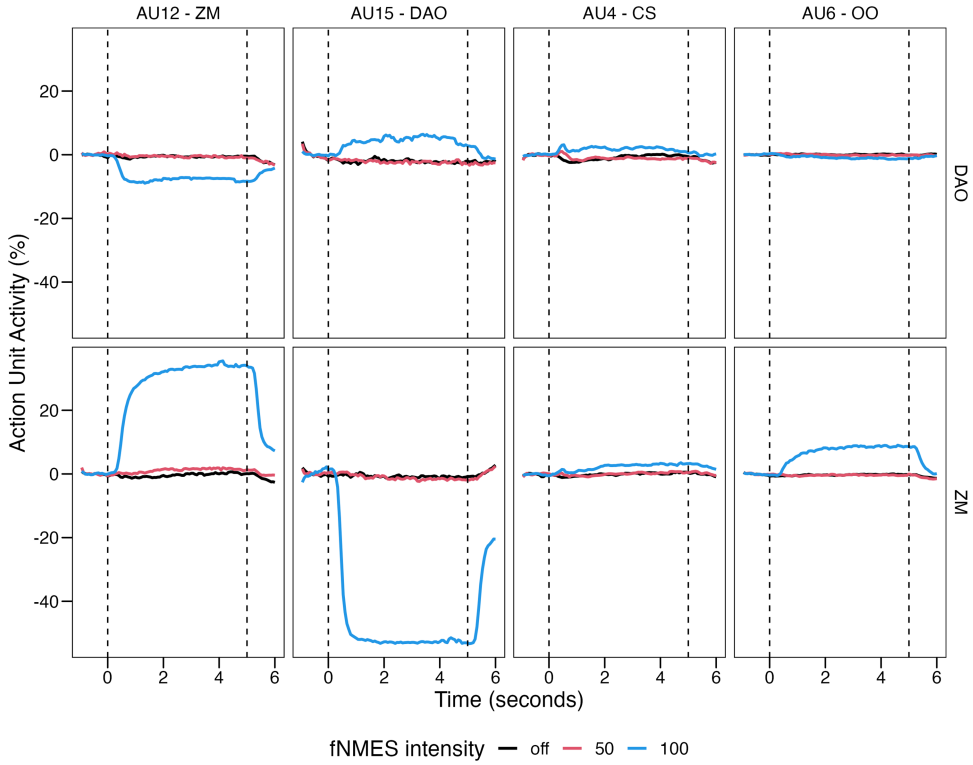
Our primary model to analyze self-reported valence on a trial-by-trial basis included the predictors fNMES (continuous), image (categorical with levels congruent, neutral, no image), and the covariates positive affect (measured with the Positive and Negative Affect Schedule at the beginning of the experiment) and discomfort (measured after each trial and averaged per participant), which were selected based on model fit comparisons (see Supplemental Table S3 for details). The model (formula: valence ~ fNMES + fNMES: image + positive affect + discomfort) produced substantial explanatory power (conditional $R^2 = .68$, marginal $R^2 = .28$). Planned comparisons were conducted using contrast treatments for image congruent trials.

In line with Hypothesis 1, we found a significant main effect of fNMES on self-reported emotional valence, $\beta = 0.44$, $SE = 0.03$, 95% CI [0.39, 0.50], $t(976.35) = 15.76$, $p < .001$, suggesting, as expected, a linear increase in valence from DAO 100% of MT with the highest valence at ZM 100% of MT. Second, in line with Hypothesis 2, an fNMES by image interaction emerged. The size of the fNMES effect on valence of felt emotion was greater (steeper slope) in the congruent image compared to both the neutral image, $\beta_{diff} = 0.42$, $SE = 0.04$, $t(976) = 10.55$, $p < .001$ and the no image, $\beta_{diff} = 0.37$, $SE = 0.04$, $t(976) = 9.56$, $p < .001$, conditions, but the neutral and no-image conditions did not differ, $\beta_{diff} = -0.04$, $SE = 0.04$, $t(976) = 1.08$, $p < .577$. This suggests (see Figure 3A) that fNMES resulted in the expected changes in emotional valence, both when provided without images (dashed green line) and to an even bigger extent when combined with an emotionally congruent image (solid blue line). This was also confirmed by comparing slopes against 0. The slope for the congruent image condition was significantly greater than 0, $\beta = 0.44$, $SE = 0.03$, $t(976) = 15.76$, $p < .001$, and so was the one for the no-image condition, $\beta = 0.06$, $SE = 0.03$, $t(976) = 0.86$, $p = .023$. The neutral image condition, however, did not significantly differ from 0, $\beta = 0.02$, $SE = 0.03$, $t(976) = 2.28$, $p = .390$. This suggests that activating facial muscles did result in the expected changes in felt emotion, although the effects were much stronger when congruent emotional images were shown at the same time. Finally, both covariates had a statistically significant effect. Valence was higher for participants who started the session

[3] The pattern of results did not change when excluding the high-alexithymia participants.

Figure 2

Average Activity of Four AUs (Roughly Corresponding to the Activity of the ZM, DAO, CS, and OO Muscles) During fNMES Application to the DAO Muscle (Top Row) and the ZM Muscle (Bottom Row)



Note. This graph displays the adjusted values of four AUs after baseline correction (only trials with confidence >.95 were included) and averaged across all visual stimulus conditions. The baseline mean was subtracted from each AU. The start and end of the 5 s of fNMES are shown with vertical dotted lines. The colored lines show the intensity of the stimulation: 100%, 50%, and 0% (off) of MT. AU = action unit; ZM = zygomaticus major; DAO = depressor anguli oris; CS = corrugator supercilli; OO = orbicularis oculi; fNMES = facial neuromuscular electrical stimulation; MT = motor threshold. See the online article for the color version of this figure.

with higher levels of positive affect, β = 0.31, *SE* = 0.08, 95% CI [0.16, 0.46], $t(56) = 4.01$, $p < .001$, and lower for participants who reported high levels of discomfort, β = −0.24, *SE* = 0.02, 95% CI [−0.28, −0.20], $t(1{,}001) = 12.10$, $p < .001$.

To analyze self-reported intensity, we included the same predictors as for the valence analysis and obtained a good fit (conditional R^2 = .62, marginal R^2 = .20). Only the covariates had significant effects. We found that greater emotional intensity was predicted by higher levels of positive affect in the Positive and Negative Affect Schedule, β = 0.23, *SE* = 0.08, 95% CI [0.08, 0.39], $t(56) = 3.01$, $p = .004$, and by greater self-reported discomfort, β = 0.36, *SE* = 0.02, 95% CI [0.32, 0.40], $t(976) = 17.18$, $p < .001$. No other main or interaction effects were observed (all βs < 0.08 and *p*s > .060).

We conducted additional preregistered analyses that compared self-reported valence and intensity between the fNMES conditions DAO 100%, off, and ZM 100%, treating them as categorical variables. The same covariates as in the previous models were used. For valence, significant main effects of positive affect, $F(1, 56) = 15.89$, $p < .001$, and discomfort, $F(1, 668) = 57.84$, $p < .001$, were found. An interaction between fNMES and image also emerged, $F(8, 627) = 18.48$, $p < .001$. Overall, differences in valence between fNMES conditions only emerged for the conditions where an image was presented (see Table 1), although the DAO 100%–ZM 100% contrast was at significance threshold ($p = .05$) in the no-image condition. Not surprisingly, statistical significance of the "pure" fNMES effect (no-image condition) was thus reduced when treating fNMES as a categorical predictor, which takes more degrees of freedom, compared to treating it as a continuous predictor. For intensity, we found significant main effects of positive affect, $F(1, 55) = 8.22$, $p = .006$, and discomfort, $F(1, 670) = 50.00$, $p < .001$, and an interaction between fNMES and image, $F(8, 626) = 7.49$, $p < .001$, suggesting greater emotional intensity in conditions where fNMES was at 100% of MT (see Table 1). In summary, results of the analyses treating fNMES as a categorical variable led to the same pattern of results obtained when entering fNMES as a continuous predictor.

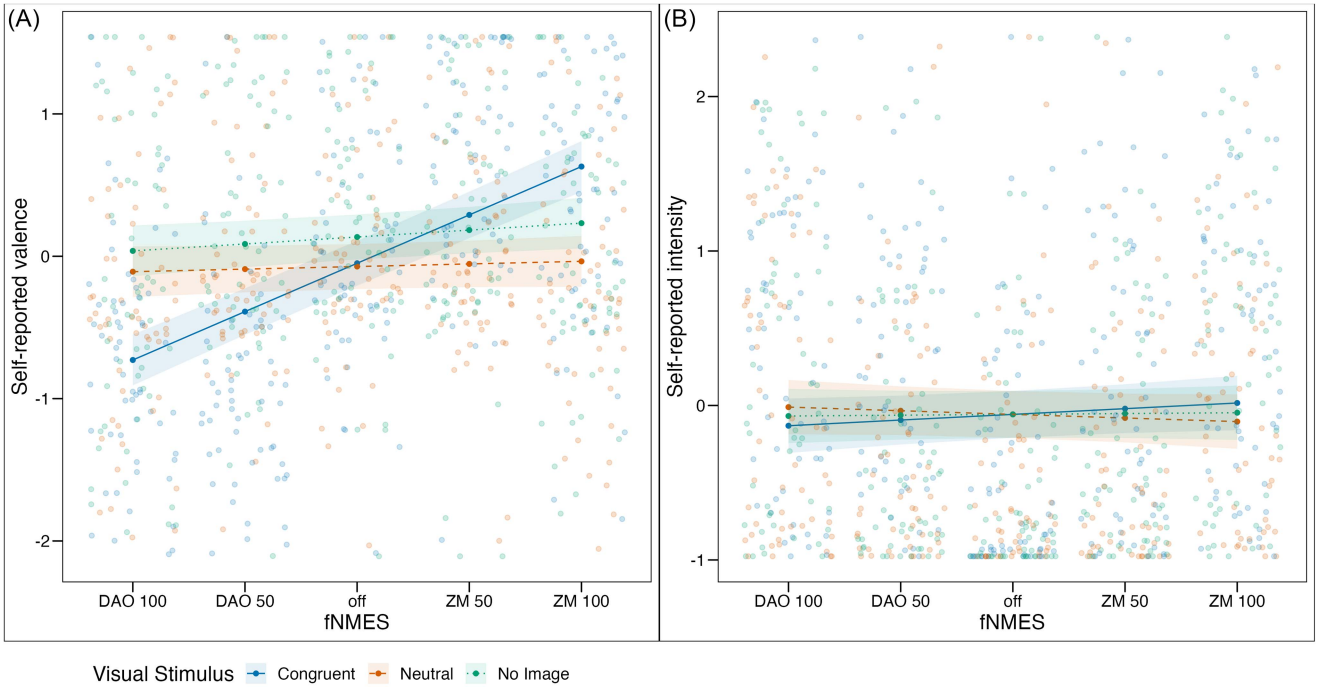
Physiological Results

Models to investigate trial-wise differences in HR and SCR included the muscle stimulated (ZM and DAO), the intensity of the stimulation (off, 50%, and 100% of the MT), and the image shown (no image, neutral, incongruent, congruent emotion).

For SCR, we found (see Figure 4) a main effect of muscle, $F(1, 776) = 7.18$, $p = .008$, with a larger SCR when the ZM ($M = -1.33$,

Figure 3

Effects of fNMES Condition and Visual Stimulus on Valence (A) and Intensity (B)



Note. Individual data shown as lighter points, jittered for clarity. The darker points, connected through fit lines, represent the marginal means for each fNMES level. Shaded ribbons indicate the standard error. fNMES = facial neuromuscular electrical stimulation; DAO = depressor anguli oris; ZM = zygomaticus major. See the online article for the color version of this figure.

$SE = 0.24$), compared to DAO muscle, was targeted ($M = -1.86$, $SE = 0.24$). A significant main effect of fNMES was also found, $F(2, 776) = 55.21$, $p < .001$. Planned contrasts showed a larger SCR for the 100% MT condition ($M = -3.00$, $SE = 0.26$) compared to 50% MT, $M = -1.25$, $SE = 0.26$, $t(869) = 7.05$, $p < .001$, and off, $M = -0.54$, $SE = 0.26$, $t(870) = 10.32$, $p < .001$. No other main or interaction effects emerged (all Fs < 2.25 and all ps > .081).

For HR, fNMES intensity emerged as statistically significant, $F(2, 775) = 4.57$, $p = .011$. Specifically, HR was faster in the fNMES off ($M = 74.79$, $SE = 1.27$) compared to the fNMES 100%

Table 1

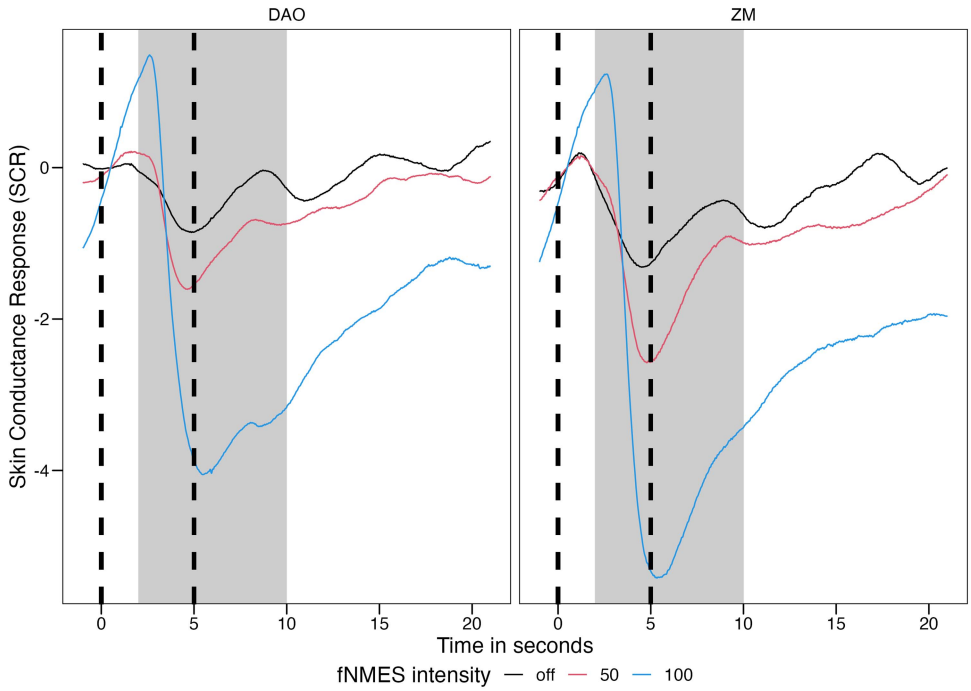
Bonferroni-Corrected Post Hoc Comparisons of Self-Reported Valence and Intensity by fNMES Conditions and Image

Outcome	Image	Contrast	M_{diff}	SE	df	t	p
Valence	Congruent	DAO 100—off	−0.40	0.10	638	4.17	<.001
		DAO 100—ZM 100	−1.01	0.09	624	10.71	<.001
		Off—ZM 100	−0.62	0.09	634	6.74	<.001
	Neutral	DAO 100—off	0.05	0.09	634	0.58	1
		DAO 100—ZM 100	−0.08	0.09	623	0.80	1
		Off—ZM 100	−0.13	0.09	636	1.36	.519
	No image	DAO 100—off	−0.10	0.09	635	1.05	.888
		DAO 100—ZM 100	−0.23	0.09	623	2.40	.050
		Off—ZM 100	−0.13	0.09	636	1.38	.504
Intensity	Congruent	DAO 100—off	0.36	0.10	638	3.60	.001
		DAO 100—ZM 100	−0.09	0.10	624	0.94	1
		Off—ZM 100	−0.45	0.10	635	4.74	<.001
	Neutral	DAO 100—off	0.23	0.10	635	2.41	.049
		DAO 100—ZM 100	0.08	0.10	623	0.77	1
		Off—ZM 100	−0.16	0.10	637	1.59	.335
	No image	DAO 100—off	0.49	0.10	636	5.06	<.001
		DAO 100—ZM 100	−0.01	0.10	623	0.14	1
		Off—ZM 100	−0.50	0.10	637	5.13	<.001

Note. fNMES = facial neuromuscular electrical stimulation; SE = standard error; DAO = depressor anguli oris; ZM = zygomaticus major.

Figure 4

Changes in SCR Over Time for Each Target Muscle and fNMES Intensity



Note. SCR by muscle and fNMES condition, averaged across all visual stimulus conditions. fNMES was delivered from 0 to 5 s, as indicated by dashed lines. The shaded area highlights the region of interest averaged for statistical analysis (2–8 s). fNMES = facial neuromuscular electrical stimulation; DAO = depressor anguli oris; ZM = zygomaticus major. See the online article for the color version of this figure.

of MT condition, $M = 73.99$, $SE = 1.27$, $t(775) = 2.99$, $p = .009$. No other main or interaction effects emerged (all Fs < 2.09 and all ps $> .111$).

To test Hypotheses 5 and 6, we fitted separate LMMs to compare differences in HR (conditional $R^2 = .49$, marginal $R^2 = .00$) and SCL (conditional $R^2 = .24$, marginal $R^2 = 0.00$) between muscles (formula: HR/SCL ~ Muscle). There were no statistically significant differences between the ZM and DAO blocks in either HR, $\beta = -0.27$, $SE = 0.57$, $t(47) = 0.47$, 95% CI [−0.43 0.70], $p = .640$, or SCL, $\beta = 3.68$, $SE = 56.63$, 95% CI [−1.40, 0.86], $t(47) = .07$, $p = .950$, suggesting that tonic SCL and HR were unaffected by the muscle being stimulated.

Exploratory Analyses

Additional exploratory analyses were carried out without directional predictions. These were not preregistered. Sum contrasts were used, and outputs were reported using Type 3 analyses of variance.

First, a paired t test showed that mood (measured with a VAS at the start of each block) did not differ across blocks, $M_{diff} = 0.21$, 95% CI [−0.05, 0.47], $t(57) = 1.63$, $p = .108$. Second, we investigated possible changes in levels of discomfort between fNMES conditions with an LMM including the categorical predictors of fNMES intensity (off, 50 and 100% of MT) and muscle (DAO, ZM) and mood at the start of each block as a covariate. A statistically significant main effect of fNMES intensity, $F(2) = 530.99$, $p < .001$, was followed up with Bonferroni-corrected post hoc comparisons using the emmeans function. fNMES at 100% of MT ($M = 0.76$, $SE = 0.07$) produced higher levels of discomfort compared to 50%, $M = -0.24$, $SE = 0.07$, $t(974) = 23.48$, $p < .001$, and off, $M = -0.58$, $SE = 0.07$, $t(974) = 31.30$, $p < .001$. Additionally, 50% of MT resulted in greater discomfort than off, $t(974) = -7.92$, $p < .001$. Further, the main effect of muscle was statistically significant, $F(1) = 8.62$ $p = .003$, with self-reported discomfort being greater when stimulation was applied to the DAO ($M = 0.03$, $SE = 0.06$) compared to the ZM ($M = -0.07$, $SE = 0.06$). This effect was, however, driven by muscle differences at 50% intensity only, as shown by an intensity by muscle interaction, $F(2) = 5.90$, $p = .003$; see Table 2. In summary, stimulation of the DAO was rated as more uncomfortable but only for the weaker current of 50% MT; when

Table 2

Post Hoc Comparisons of Self-Reported Discomfort by Muscle and fNMES Intensity

fNMES intensity	Contrast	M_{diff}	SE	df	t	p
Off	DAO—ZM	0.01	0.06	982	0.16	.870
50	DAO—ZM	0.28	0.06	982	4.51	<.001
100	DAO—ZM	0.03	0.06	982	0.53	.598

Note. fNMES = facial neuromuscular electrical stimulation; SE = standard error; DAO = depressor anguli oris; ZM = zygomaticus major.

fNMES was delivered at 100% of MT, discomfort increased but was similar for both muscles.

Finally, we used an LMM (formula: valence ~ muscle + discomfort) to investigate block effects on valence ratings, irrespective of fNMES intensity. We found (conditional $R^2 = .74$, marginal $R^2 = .16$) higher valence in the ZM compared to the DAO block, $\beta = 0.27$, $SE = 0.05$, 95% CI [0.18, 0.36], $t(293) = 5.76$, $p < .001$, suggesting an overall shift in participants' mood during each block. Further, there was a main effect of discomfort, $\beta = -0.55$, $SE = 0.09$, 95% CI [−0.71, −0.39], $t(342) = 6.58$, $p < .001$, reflecting lower valence for higher discomfort. In summary, valence was larger in the ZM block when controlling for fNMES-induced discomfort, which suggests that 20–30 min of ZM activation can improve mood. However, one should keep in mind that these fNMES effects are confounded with the (larger) image effects.

Discussion

Much of the extant scientific literature suggests that facial expressions and emotional feelings are bidirectionally linked and that the simulation of an emotional facial expression (e.g., through voluntary posing or the pen-in-mouth technique) can initiate and/or modulate the corresponding feelings (Coles et al., 2019; Wood et al., 2016). However, facial feedback effects are small and heterogeneous (Coles et al., 2019), seminal findings have not been replicated (Wagenmakers et al., 2016), and it remains debated exactly what role facial feedback has in generating and modulating affective responses. With the goal of using a more controlled alternative to common facial feedback manipulations (e.g., expression posing, pen-in-mouth, Botox), this study set out to examine whether fNMES-induced activation of muscles involved in smiling and frowning could trigger self-reported positive and negative emotional states, respectively. Additionally, we investigated two intensities of fNMES and if the resulting muscle activation can modify ongoing emotional states elicited by emotional visual stimuli. Last, we examined if changes in emotional states corresponded to changes in the physiological measures of HR, SCL, and SCR.

Results confirmed the main hypothesis (Hypothesis 1) that self-reported valence would increase over the five levels of fNMES muscle and intensity. We indeed found a significant main effect of fNMES (which was entered as a continuous predictor with the levels DAO 100%, DAO 50%, off, ZM 50%, and ZM 100%) on valence. Participants' self-reported emotional valence was modulated by the combination of target muscle and stimulation intensity, with the highest and lowest ratings, respectively, occurring for ZM and DAO stimulation at 100% of MT, and the other fNMES conditions resulting in intermediate levels of valence (Figure 3A). A similar pattern was obtained when fNMES was entered as a categorical predictor with three levels (DAO 100%, off, and ZM 100%)—the weaker and mostly nonsignificant effects are explained by the fact that this analysis requires more degrees of freedom, for which we had not powered the experiment (see power analysis and sample size justification in the Method section).

This result indicates that fNMES can elicit emotional states independently of concurrent visual stimuli, consistent with prior research demonstrating that posing emotional facial expressions can initiate a corresponding emotional experience (Coles et al., 2023). In line with a recent meta-analysis on facial feedback effects (Coles et al., 2019), the effect of fNMES on self-reported valence was small. The effect is nevertheless noteworthy, given that it persisted after controlling for initial positive mood and fNMES-related discomfort and that it was obtained through weak contractions of the ZM and DAO muscles; even at 100% of MT, only small movements were visible. Instead, facial muscles were activated to much greater extent in previous research (Coles et al., 2022, 2023). Furthermore, the present study is the first study to establish that fNMES alone can modulate the valence of felt emotion; in contrast, fNMES was administered in addition to voluntary posed smiles in past research (Kapadia et al., 2019; Zariffa et al., 2014). Finally, it is the first study to suggest that the valence of felt emotion can be both increased and decreased, depending on whether muscles associated with smiling or sadness are targeted, respectively.

In line with Hypothesis 2, fNMES also modulated emotions elicited by the presentation of stimulation-congruent images (positive for the ZM block and negative for the DAO block), as indicated by a significant fNMES by image interaction. The effect of fNMES on valence ratings was indeed much stronger when images of congruent emotions were shown at the same time (Figure 3A). Importantly, however, the pure fNMES effect remained significant in the condition without images.

Interestingly, we did not observe facial feedback effects when participants were exposed to neutral images. Although this is consistent with Warren (2021), it remains surprising that neutral images, which arguably do not elicit emotions, lead to the elimination of the fNMES effect. Indeed, past research in this domain presents mixed results: Some studies proposed that facial feedback effects can initiate emotional states in the presence of neutral stimuli (Adelmann & Zajonc, 1989; McIntosh, 1996; Mori & Mori, 2009). Others, however, have been unable to replicate this effect and have even suggested that the lack of consistency may stem from the presentation of neutral and emotional stimuli in the same block (Dimberg & Söderkvist, 2011), a point that also applies to our study. The reason is that mixing of emotion categories may influence participants' expectations. Moreover, prior research shows that emotional intensity ratings are significantly influenced by preceding cues (e.g., expecting to see a sad image might intensify a mildly sad picture), suggesting that attention plays a role in shaping subjective experiences of emotional stimuli (Bermpohl et al., 2006).

In addition to self-report, we also measured participants' phasic (SCR, HR) and tonic (SCL) physiological responses. Interestingly, there was a short-lived positive spike in skin conductance (Figure 4), potentially reflecting a startle response (Alaoui-Ismaïli et al., 1997; Collet et al., 1997). However, the overall the effect on SCR was a large decrease in SCR when fNMES was delivered at 100% of MT, compared to the 50% and off conditions, indicating a decrease in skin conductivity—a finding that is often associated with relaxation or lower arousal (Christopoulos et al., 2019). Discomfort or pain would not explain this decrease, as they typically cause a positive SCR increase (Storm, 2008). We also observed differences in SCR by muscle, with a larger negative response in the ZM compared to the DAO muscle across all conditions. This may be explained by facial feedback effects—that is, the act of smiling in ZM trials resulted in an increase in happiness (as also shown by participants' ratings), enhancing the difference consistent with the FFH (Kreibig, 2010; Soussignan, 2002). This is particularly noteworthy since the image condition did not significantly influence changes in SCR.

Furthermore, the trial-wise analysis revealed that HR significantly decreased in trials with fNMES at 100% of MT, compared to off

trials. This finding is partially consistent with prior research on the FFH and its influence on stress recovery. Specifically, a study by Kraft and Pressman (2012) found that participants instructed to smile using the pen-in-mouth technique exhibited lower HR during recovery from a stressful task, compared to those who maintained neutral facial expressions. However, we observed this difference across both ZM and DAO trials. An alternative explanation for the observed decrease in HR, even in the absence of deliberate emotional induction, could be a physiological "freezing" response, as described by Gladwin et al. (2016). This response, often an automatic orienting reaction to unexpected stimuli, involves a temporary reduction in heart rate as part of the body's initial evaluative process of the stimulus, potentially triggered here by the sensation of fNMES itself. Overall, it is difficult to align the findings on facial feedback on HR due to the limited research in this area, as to date this is the first study to investigate fNMES-induced facial feedback effects on HR and SCR.

No significant differences in block-wise HR or SCL were found across any of the conditions (fNMES targeting ZM or DAO muscle at different intensities, or no stimulation), possibly due to the long window of analysis (approximately 15 min per muscle block). This might have contributed to the weakening of potential effects of fNMES on physiology, as facial feedback effects are known to be rather short-lived (Dimberg & Söderkvist, 2011). Furthermore, such effects might have been masked by the mixed presentation of positive, negative, and neutral stimuli in the block. A possible explanation for the mixed bag of physiological results found here is that the effects of faint fNMES-induced muscle activation on physiology may be very small and require larger sample sizes (our study was powered for the main effect of fNMES on valence and not for these physiological analyses). Nevertheless, further investigation into the optimal timing of physiological response measurements in relation to fNMES application, and the potential for shorter block durations to isolate potential effects, is needed.

This study has demonstrated that fNMES stands out, in comparison to other means of manipulating facial feedback, through the high level of control it offers. Specifically, we were able to induce specific bilateral facial movements (as confirmed with Facial Action Coding System) at specific times and intensities, and we were able to capture its effects on participants' felt emotion. We also found increased HR and decreased SCR in trials with stronger fNMES (100% of MT). Not only do these results support the FFH, but they also show the great potential for using computer-controlled fNMES to investigate other facial feedback effects. For example, we recently found that emotionally ambiguous faces tend to be perceived as happy when presented together with 500 ms of fNMES over the ZM muscles (Efthimiou, Baker, et al., 2024).

At the same time, several limitations of our work should be noted. First, we induced small changes in expression and stimulated only one muscle for each expression, while genuine (Duchenne) smiles typically involve the OO in addition to the ZM, and sadness expressions also involve several muscles, of which the DAO is not always a part of (e.g., Wingenbach et al., 2020, did not find DAO activation during facial mimicry of sadness). Stronger effects may be observed if several muscles are stimulated at the same time to more closely reproduce genuine emotional expressions. In relation to that, smaller facial feedback effects were found for smiles involving the ZM but lacking OO activation (Kraft & Pressman, 2012; Soussignan, 2002), suggesting that stronger effects can be achieved if fNMES is applied conjointly to the ZM and OO muscles. Second, fNMES-induced discomfort affected participants' experience and resulted in lower ratings of emotional valence. Although we did control for discomfort by including it as a covariate, it would have been ideal to eliminate this factor entirely. Previous research by Warren (2021) addressed this concern by using weaker electrical stimulation (below MT, maybe comparable to our 50% condition), but this does not fully test the FFH, as muscle activation and changes in proprioceptive feedback may not be induced at those weak intensities. However, the discomfort issue could be addressed by further optimizing the fNMES parameters. As noted by Efthimiou, Hernandez, et al. (2024), there is no current consensus on the optimal fNMES parameters, so further research is needed to determine the most effective and comfortable combinations of waveform, pulse width, and stimulation frequency. Third, the physiological methods employed here may not have been sensitive enough to detect the subtle effects induced by fNMES. Indeed, recent findings suggest that emotional responses are captured better by brain activity—measured with neuroimaging techniques like functional magnetic resonance imaging—than by peripheral physiology measures, like HR (Wilson et al., 2020). This underscores the limitations of traditional physiological measurements for detecting such nuanced effects. Therefore, future research should integrate neuroimaging tools, including functional magnetic resonance imaging and EEG, with fNMES. These combined methodologies can help pinpoint brain regions involved in the integration of face perception, facial feedback, and emotional experience, providing a deeper understanding of the underlying mechanisms (Baker et al., 2023). Finally, no positive images were shown in the DAO block, and the ZM block lacked negative images. This was done to reduce the number of trials and the amount of current delivered; however, it restricted the possible statistical comparisons, such as the effects of fNMES-induced smiling while seeing negative images. Future research should delve deeper into these effects while also employing different types of visual stimuli (e.g., complex, dynamic).

Future research should consider the role of social context in facial feedback. This study investigated the effects of fNMES in a controlled lab setting, but real-world emotional experiences often occur during social interactions. It would be interesting to see if the findings hold true when participants are interacting with others. Social cues and feedback from others could potentially amplify or dampen facial feedback effects, adding another layer of complexity to the relationship between facial expressions and emotions (Phaf & Rotteveel, 2023). Furthermore, it is plausible that repeated fNMES sessions could result in more durable benefits. This is supported by Kapadia et al. (2019), who found that multiple fNMES sessions helped reduce depressive symptoms, suggesting that small effects can accumulate into significant improvements through consistent use. Second, fNMES may have a more pronounced benefit for individuals with certain neurological conditions or emotional dysregulation disorders (amplification through interaction). For example, patients with facial paralysis may experience greater benefits due to their lack of spontaneous facial mimicry—a deficit that fNMES can help address. These effects might appear negligible when evaluated on a broad scale but could nevertheless be quite profound for these subgroups.

In summary, our study supports the FFH by showing that positive and negative emotion can be triggered through activation of smiling and frowning muscles. Moreover, it contributes valuable evidence

to the growing body of literature supporting the efficacy of fNMES in influencing emotional experiences and physiology through precise facial feedback modulation. Our study highlights the potential for fNMES to effectively generate and influence emotions, with potential implications for diverse fields such as brain–computer interfaces and mental health (Goto et al., 2018; Kapadia et al., 2019).

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