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Controlling the emotional heart:

Heart rate biofeedback improves cardiac control during emotional reactions.

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Abstract

When regulating negative emotional reactions, one goal is to reduce physiological reactions. However, not all regulation strategies succeed in doing that. We tested whether heart rate biofeedback helped participants reduce physiological reactions in response to negative and neutral pictures. When viewing neutral pictures, participants could regulate their heart rate whether the heart rate feedback was real or not. In contrast, when viewing negative pictures, participants could regulate heart rate only when feedback was real. Ratings of task success paralleled heart rate. Participants' general level of anxiety, emotion awareness, or cognitive emotion regulation strategies did not influence the results. Our findings show that accurate online heart rate biofeedback provides an efficient way to down-regulate autonomic physiological reactions when encountering negative stimuli.

Keywords: biofeedback; heart rate; arousal control; cardiac control; emotion regulation.

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Heart rate biofeedback improves arousal control during emotional reactions.

In some situations, a full blown uncontrolled emotional reaction may obstruct goal-directed behavior, for example when giving a speech in front of an audience and suddenly experiencing intense anxiety. In such situations, a good option is to try to regulate the emotional reaction. Emotional reactions are multifaceted and can be divided into three fundamental components: behavioral expression, subjective experience and physiological reaction, such as arousal or tension. Different regulation strategies target one or several of these components and have different success rates in regulating them (John & Gross, 2004). For example, regulating emotions by means of suppression has been found to have no or even opposite effect on physiological reactions (Gross & Levenson, 1993; Demaree, Schmeichel, Robinson, Pu, Everhart, & Berntson, 2006; Roberts, Levenson & Gross, 2008). In addition, the perception of physiological reactions seem altered in individuals with anxiety disorders and has been proposed to be a key vulnerability factor in the etiology and maintenance of state and trait anxiety as well as anxiety sensitivity and anxiety disorders (Domschke, Stevens, Pfleiderer & Gerlach, 2010). It has also been suggested that unregulated physiological reactions increase the long-term risk for cardiovascular disease (Mauss & Gross, 2004).

These findings emphasize the need to develop ways by which physiological reactions during the experience of negative emotions can be regulated efficiently in order to prevent the organism from prolonged experience of arousal and negative affect. In this context, biofeedback appears especially valuable because it consists of directly feeding back relevant information about the current state of physiological reactions evoked by specific stimuli or situations to the individual. This information usually conveyed by sight or hearing, can be for example muscle activity (Electromyography, EMG), heart rate (HR), blood pressure, or skin conductance (SC). Through biofeedback, the individual can get online information about physiological activity and eventually learn to use this information in order to regulate it, and in turn influence emotion processing.

There are numerous studies that have shown that physiological reactions can be controlled by means of biofeedback in non-emotional situations (Blanchard & Young, 1973; Critchley, Melmed, Featherstone, Mathias & Dolan, 2002; Futterman, & Shapiro, 1986; Heffernan-Colman, Sharpley, King, 1992). Regarding emotional situations, biofeedback has been used in different ways in clinical settings. Biofeedback has been utilized to train participants to control their heart rate and influence it later during a speech task performed without feedback (Gachel & Proctor, 1976; Gatchel, Hatch, Maynard, Turns, & Taunton-Blackwood, 1979). Compared to training with an active control condition, biofeedback training resulted in a lower heart rate and reduced self-reported anxiety (Gachel & Proctor, 1976). Compared to false biofeedback training and relaxation training, biofeedback training resulted in lowered heart rate but self-reported anxiety was the same in these three groups (Gatchel, Hatch, Maynard, Turns, & Taunton-Blackwood, 1979). Biofeedback has also been used to bring attention to the process of habituation during an exposure session and was found to reduce participants' claustrophobic fear ratings compared to paced tone and exposure only (Telch, Valentiner, Ilai, Petruzzi, & Hehmsoth, 2000).

Another way of using biofeedback to reduce emotional arousal is to use it as a feedback informing about the actual efficiency of the emotion regulation strategy used by the participant at a given moment in time. If the strategy happens to be inefficient, the psychophysiological information fed back online to the participant will encourage him/her to change his/her strategy. As such, a successful regulation can be achieved through the use of a flexible strategy. In such scenario, biofeedback needs to be provided online to the individual in order to immediately link this bodily information to the efficiency of the current regulation strategy used by him/her. Recent technological advancements (e.g., portable pulse watches) make it possible nowadays to rely on the online monitoring of physiological responses to implement regulation processes aimed at downplaying bodily arousal. The added value of this approach is that the best regulation strategy can be optimized for each and every individual, despite a large variability across individuals in their physiological responses to arousal. Accordingly, the present study might therefore complement these earlier studies by showing that heart rate biofeedback provides a valuable tool to down-regulate physiological responses to evocative visual stimuli in healthy participants.

To investigate if online biofeedback of heart rate can improve regulation of emotional physiological reactions, regulation of heart rate reactions to standardized emotional stimuli were measured during real and false online biofeedback. We contrasted an active heart rate regulation condition to a control condition with a simple monitoring of heart rate. Importantly, to rule out the possibility of unspecific effects during the regulation of the heart rate, we used a stringent cross-over design and unknowingly to the participants alternated real accurate heart rate feedback and fake feedback between blocks. We used standard (i.e. previously validated) neutral vs. negative emotion-eliciting pictures. Neutral stimuli were used as a control condition and directly compared to unpleasant pictures for which a clear directional effect in terms of physiological reactions was expected a priori (unlike the neutral pictures for which we did not predict any change along this dimension). In the study, we considered potential moderating effects of general anxiety and emotion awareness, measured using standard questionnaires, on the regulation of the heart rate. Likewise, given that different emotion regulation strategies may have different effects on the success to control physiological arousal (John & Gross, 2004), we also assessed whether inter-individual differences in emotion regulation strategies may have influenced the ability to regulate heart rate during negative affect.

In this study, biofeedback was explicitly based on heart rate, as opposed to skin conductance for example, in order to minimize the delay between the changes in physiological activity and the visual feedback information provided to the participants. Heart rate as feedback measure also has the advantage over skin conductance of being more available in real life through portable devices such as pulse watches. However, while skin conductance responses to negative arousing stimuli are unidirectional, heart rate responses are not. Heart rate responses to negative arousing stimuli first decelerate after stimulus onset (reflecting an orienting response). After this initial deceleration, with increased arousal, heart rate then accelerates and later decelerates again (Fredrikson, 1981; Lang, Davis, & Öhman, 2000). Heart rate accelerations are related to fear and are exaggerated in disorders such as specific phobia, social anxiety, post-traumatic stress disorder and panic disorder (Cuthbert, Lang, Strauss, Drobes, Patrick, & Bradley, 2003), as well as during distress and forms an integrated part of the stress response (Al'Absi, 1997). Accordingly, decreasing heart rate might very well affect core physiological reactions associated with stress and anxiety. For all these reasons, we therefore instructed participants to decrease heart rate in our study.

To summarize, the aim of the present study was to investigate whether online heart rate biofeedback could improve control over physiological responses to standard negative stimuli. We predicted that regulation of heart rate to negative pictures would improve with real as compared to fake feedback of heart rate.

Method

Ethics statement

The study was approved by the local ethics committee (Faculty of Psychology – Ghent University) and conducted in accordance with the declaration of Helsinki. Participants were informed about the voluntary nature of participation, signed an informed consent form prior to the experiment, and were fully debriefed about the purpose of the study at the end of the experiment. No participants were under the age of 18.

Participants

Twenty-three undergraduate students from Ghent University were recruited for the experiment. Participants were compensated 12 euros for participating and the experiment lasted about 1.5 hours. The data from one participant were discarded because of disbeliefs in the feedback and a regulation strategy consisting of looking away from all negative pictures. Thus, the final sample included twenty-two participants (20 women).

Apparatus and materials

Set up. The experiment was conducted in a sound-attenuated room with the experimenter sitting in a separate room. Pictures were presented at a distance of 0.6 m on a cathode ray-tube (CRT) monitor (21 inches, 1024 x 768 pixels resolution) with software written in Presentation 10.3 (Neurobehavioral Systems, www.neurobs.com). Refresh rate was set at 80Hz. ECG was recorded with Biopac MP150 system with a sampling rate of 200 Hz in standard lead II configuration: The right arm electrode was placed near the right collarbone, and the left and right leg electrodes on the right and left side of participants' ribcage. Heart rate was calculated online with Acqknowledge software. For triggers and heart rate feedback, the experiment computer and the computer hosting Acqknowledge software were connected with each other using a parallel port.

Picture material. Forty negative and 40 neutral pictures were selected from the IAPS (Lang, Bradley, & Cuthbert, 2008) based on the normative ratings provided for this data base. Negative pictures (arousal between 6.3 and 10, valence between 3.8 and 1.7) were pre-selected in such a way to include as many fear related pictures as possible and avoid mutilations because these are related to disgust responses and as such general deceleration in heart rate (Rozin, Haidt, & McCauley, 2000). Neutral pictures had arousal values ranging between 1 and 3 and valence values between 5.6 and 4.6. Pictures were 1024 x 768 pixels and scaled to 0.7 of the standard size in Presentation software (i.e. 717 x 538 pixels). The space left on the edges was used for the biofeedback information. IAPS numbers of the selected pictures were: 1050, 1052,1120,1201, 1300, 1304, 1525, 1930, 2811, 3500, 3530, 6210, 6230, 6231, 6250, 6250.1, 6260, 6263, 6300, 6313, 6315, 6350, 6360, 6370, 6510, 6520, 6540, 6550, 6560, 6563, 8485, 9163, 9187, 9250, 9413, 9414, 9635.1, 9810, 9908, 9921, 2038, 2190, 2393, 2397, 2411, 2570, 2840, 2880, 2890, 5390, 5510, 5520, 5530, 5731, 5740, 7010, 7026, 7030, 7035, 7040, 7041, 7050, 7053, 7059, 7080, 7090, 7100, 7140, 7150, 7161, 7179, 7187, 7205, 7217, 7233, 7235, 7490, 7491, 7705, 7950.

Biofeedback. Biofeedback was given to the participants by changing the background color of the screen every 500 ms. The target picture was presented in the center of the screen and did not change, only the color of the edges (top and bottom: 115 pixels or 4.8 cm; right and left edges: 153 pixels or 6.4 cm) and changed according to the updated heart rate. Participants received either real or fake feedback. The real feedback reflected participant’s actual heart rate changes and was presented in the form of background color changes on the screen. In the Acqknowledge software of the Biopac module, heart rate was computed online and was monitored by a calculation channel. When heart rate changed more than 0.1 bpm, the calculation channel sent a signal through the parallel port to the Presentation computer. The presentation software monitored the parallel port and updated the color of the screen accordingly every 500 ms. If heart rate accelerated the color was changed towards red while if it decelerated it was changed towards green. The color change was made by adjusting the red and green values of the RGB of the screen by 40 steps (the values of the RGB each ranged from 0 to 255). Each trial started at yellow (R = 255; G = 255; B = 0). To turn the screen more red, the G value was decreased. To turn the screen more green, the R value was decreased. The fake feedback was presented in the same way as the real feedback but consisted of a selection of prerecorded heart rate reactions to the same picture set from a different set of participants. The fake feedback was the same for both task types (i.e. regulate and monitor) but differed depending on the picture type. When viewing negative pictures, the fake feedback shown corresponded to prerecorded heart rate reactions (of another participant) to the same negative pictures, and vice versa for neutral pictures. Both fake feedback types consisted of a list of 10 recordings that were preselected to have a mean heart rate change of 0 and a positive mean (i.e. accelerating heart rate) on half of the recordings and a negative mean (i.e. decelerating heart rate) on the other half of the recordings. For each fake feedback trial during the experiment, the feedback was selected randomly from the corresponding list of recordings. The same list of recordings was used for both tasks (i.e. monitor and regulate) with each recording presented once for each task.

To verify that participants were actually unaware of the fake/real feedback manipulation across condition, a post experiment debriefing was conducted. Participants were asked to rate if they felt that the feedback was related to their actual heart rate, how many times they happened to be surprised by the feedback, why they thought that was, and if they suspected that something went wrong with the feedback. If they happened to raise any doubts, then they were asked to comment on what reason they thought was behind the delivery of a "strange"/unusual feedback, how often it happened and if it happened blockwise or randomly. Participants were defined as aware of the fake feedback condition if they either stated that the feedback was fake or manipulated, or if they got surprised or doubted the veracity of the feedback in more than 30 % of the trials in a blockwise manner. In total, only one participant was classified as aware and discarded from the subsequent analyses.

Questionnaires. Participants' general anxiety was assessed using the trait version of the State-Trait Anxiety Inventory (STAI; Spielberger, 1983). Participants' emotion awareness was assessed with the Toronto Alexithymia Scale (TAS; Meganck, Vanheule, & Desmet,

2008) and the Emotion Awareness Questionnaire (EAQ; Rieffe, Terwogt, Petrides, Cowan, Miers, & Tolland, 2008). Participants' emotion regulation strategies was assessed with the Emotion Control Questionnaire (ECQ; Roger, 1989) and the Emotion Regulation Questionnaire (ERQ; Gross, & John, 2003).

Procedure

Each trial in the experiment had the same structure, consisting of a short instruction (2s), a fixation cross (1s), a prolonged picture presentation (20s), and ratings of valence, arousal and task success (see figure 1). Ratings were performed on a 9-point scale. The scales for valence and arousal ratings showed figures from the Self-Assessment Manikin (SAM; Lang, 1980) and ratings of task success showed schematic thumbs-up and thumbs-down. Participants were instructed to either “Regulate” or to “Monitor” their heart rate during picture presentation. It was emphasized that in the monitor condition they were requested to actively avoid regulating heart rate. The instruction was repeated in blocks of 10 trials. Each 10-trial block consisted of the presentation of 5 neutral and 5 negative pictures in randomized order. The pictures were presented in the center of the screen and participants received heart rate biofeedback in the form of color changes on the edges of the screen. Thus, there were 4 main experimental conditions: regulate with real feedback, regulate with fake feedback, monitor with real feedback, and monitor with fake feedback.

Each condition was presented twice, once before and once after a short break. Each participant was randomly assigned one out of 4 possible presentation orders. The presentation orders were constructed so that each condition was presented only once in each position and participants never received the same task twice in a row. This was done to neutralize systematic order or carry-over effects as well as to prevent participants to receive successive blocks with fake heart rate feedback. After the task, participants completed computerized versions of the questionnaires.

To keep participants engaged with the task and to ensure that they correctly attended to the content of the pictures, they were asked after each trial to report what color mostly dominated the feedback during the trial (i.e. red or green). Additionally, in 1/10 of the trials, participants were asked a question regarding picture content (i.e. if the scene was outdoor or indoor). Unfortunately, because of a coding error in the script, we could not save properly responses to these catch trials.

Before the start of the experiment and after the break, participants performed a practice in which they got familiarized with the feedback and could try to decrease their heart rate. After each practice trial, participants rated task success. The practice ended when participants rated task success on the positive part of the scale (5 or above) three times in a row. The purpose of the practice blocks was to show participants that the feedback was real and that they could actively use this information to influence their heart rate.

Data processing

Heart rate was computed as the heart rate median in 2 second intervals from picture onset to offset resulting in 10 bins for each trial. Heart rate measures were also baseline corrected to the two seconds immediately before task instruction (i.e. from 4 to 2 seconds before picture onset). The initial heart rate deceleration (difference between bin 1 and bin 2) and the following acceleration (difference between bin 3 and the mean of bin 4, 5, and 6) were operationalized based on earlier work and guidelines in the psychophysiology literature (Bradley, & Lang, 2000).

Heart rate measures were scanned for artifacts offline using 3 criteria. First, an absolute criterion was used where heart rates above 150 or below 40 bpm were discarded. Second, a difference criterion was used where heart rates with a difference bigger than 35 bpm within a time window of 1000 ms were discarded. Third, a slope criterion was used where each sample point was compared to a sample point 100 ms before. The sample point was discarded if the difference was bigger than 35 bpm.

Results

Emotional responses.

When participants received real feedback about their heart rate and did not actively regulate it (i.e. real monitor condition), they showed a larger initial heart rate deceleration (computed as the difference between bin 1 and bin 2) to negative as compared to neutral pictures (mean difference = -2.25, $t(21) = 2.04$, $p = 0.054$) followed by an acceleration (computed as the difference between bin 3 and the mean of bin 4, 5, and 6; mean difference = 1.13, $t(21) = 2.22$, $p = 0.037$), replicating the previously observed pattern (Fredrikson, 1981; Lang, Davis, & Öhman, 2000). Over all conditions participants rated negative pictures as more arousing (mean difference = 2.71, $t(21) = 12.55$, $p < 0.001$) and more negative in valence (mean difference = -3.63, $t(21) = 22.09$, $p < 0.001$) than neutral pictures.

Task success.

Success ratings, tested by means of a 2 (picture type) x 2 (task) x 2 (feedback type) ANOVA. The main effects of picture type and task were significant, showing that participants experienced an overall higher task success to neutral as compared to negative pictures (mean difference = 0.70, $F(1, 21) = 55$, $p < 0.001$), and when monitoring as compared to regulating (mean difference = 0.73 , $F(1, 21) = 10.13$, $p = 0.004$). Both the two-way (picture type x feedback type; $F(1, 21) = 23.0$, $p < 0.001$) and the three-way interaction (picture type x feedback type x task; $F(1, 21) = 26.3$, $p < 0.001$) were significant. These effects were explained by lower success ratings when participants had to regulate their heart rate to negative pictures with fake feedback (see figure 2). More specifically, for negative pictures regulating with real feedback was rated as more successful than with fake feedback (mean difference = 0.86, $t(21) = 2.78$; $p = 0.011$), whereas the opposite effect was found for neutral pictures (mean difference = -0.73, *t*(21) = 3.05; *p* = 0.006). Regulating heart rate to negative pictures when the feedback was real was rated as equally successful as monitoring with real feedback (*t*(21) = 1.31; *p* = 0.204).

Heart rate regulation.

Heart rate responses, tested by means of a 2 (picture type) x 2 (task) x 2 (feedback type) ANOVA. Heart rate responses averaged over the whole trial showed that participants had lower heart rate in the condition when they had to regulate as compared to the condition when they had to monitor (mean difference = -1.57 , *F*(1, 21) = 16.43, *p* < 0.001). Hence, participants could effectively lower their heart rate when asked to do so. The main effect of feedback type was not significant (i.e. real vs. fake; *F*(1, 21) = 0.59, *p* = 0.451). Instead, the significant three way interaction (picture type x feedback type x task; *F*(1, 21) = 6.04, *p* = 0.023) indicated that the feedback type had a differential effect on participants' heart rate depending on the experimental condition. Specifically, for the neutral pictures, participants had lower heart rate when regulating compared to monitoring (mean difference = -1.73, *F*(1, 21) = 10.61, *p* = 0.004), with no interaction with feedback type (feedback type x task; *F*(1, 21) = 1.36, *p* = 0.257). Thus, these results showed that real feedback did not improve heart rate regulation for neutral pictures, compared to fake feedback. By contrast, for the negative pictures, the interaction between task and feedback type was marginally significant (*F*(1, 21) = 4.14, *p* = 0.055). This interaction effect showed that participants watching negative pictures had a lower heart rate when regulating as compared to monitoring, but only when the feedback was real (mean difference = -2.04, *t*(21) = 2.87; *p* = 0.009), but not fake (*t*(21) = 0.916; *p* = 0.370). In other words, when viewing negative pictures, participants could regulate their heart rate better if they received feedback related to their actual heart rate, as opposed to a condition where the feedback appeared to be real but was in fact fully decoupled from the actual heart rate (see figure 3 for mean responses and figure 4 for time-course of heart rate in the four conditions). In contrast, when viewing neutral pictures, heart rate feedback did not affect online regulation of heart rate.

These results for the heart rate regulation remained unchanged when only women were included in the analyses. We also performed an auxiliary analysis, excluding the initial orienting response characterized by a heart rate deceleration at the beginning of the trial (i.e. by excluding bin 1 and 2 from the analysis). Hence, this control analysis was selectively focused on the accelerative component of the heart rate response to negative vs. neutral pictures. This analysis confirmed the results reported above. It revealed a lower heart rate in regulate compared to monitor (mean difference = -1.79, $F(1, 21) = 22.04$, $p < 0.001$), no significant main effect of the feedback type (i.e. real or fake; $F(1, 21) = 0.545$, $p = 0.469$), but a significant three-way interaction (picture type x feedback type x task; $F(1, 21) = 7.14$, $p = 0.014$). For neutral pictures, changes in heart rate were mainly influenced by task (mean difference = -2.02, $F(1, 21) = 11.71$, $p = 0.003$) without modulation by feedback type (feedback type x task; $F(1, 21) = 1.36$, $p = 0.257$). For negative pictures, the interaction between task and feedback type, reported as trends significant in the analysis above, was clearly significant (feedback type x task; $F(1, 21) = 5.70$, $p = 0.026$) when the deceleration phase was excluded. The interaction effect was driven by a lower heart rate in regulate as compared to monitor only when the feedback was real (mean difference = -2.24, $t(21) = 3.28$; $p = 0.004$) but not fake ($t(21) = 1.08$; $p = 0.293$).

Individual differences

Because unregulated arousal may be associated with anxiety, we also assessed whether individual differences in trait anxiety, emotion awareness and habitual use of emotion regulation strategies somehow influenced these results. For this purpose, the scores obtained for these questionnaires were entered as separate covariates in the above described 2 (picture type) x 2 (task) x 2 (feedback type) ANOVA. This analysis failed to show a significant covariance effect of trait anxiety (STAI, $p = 0.306$) or emotion awareness (TAS, for the sum and all subscales $p > 0.381$; EAQ, for all subscales $p > 0.179$). Regarding inter-individual differences for the habitual emotion regulation strategies used by the participants, the analysis showed that only a habitual use of suppression (measured by ERQ, $F(1, 20) = 5.11$; $p = 0.035$) and inhibition of emotions (measured by a subscale of ECQ, $F(1, 20) = 9.99$; $p = 0.005$) were significant covariates, but importantly none of these two factors significantly influenced any specific experimental factor alone (main effects) or interaction effect between these experimental factors (all $p > 0.138$).

Arousal and valence ratings

Participants rated arousal and valence of the pictures after each trial. These arousal ratings were analyzed by means of a 2 (picture type) x 2 (task) x 2 (feedback type) ANOVA. This analysis showed no significant main effect or interaction with task or feedback type (all $p > 0.14$). For the valence ratings, the ANOVA revealed a significant two-way interaction between picture type and feedback type ($F(1, 21) = 5.22$, $p = 0.033$). This interaction effect was explained by the combined effect of two non-significant differences in opposite directions (i.e. participants tended to rate pictures as more negative during fake feedback compared to real feedback for neutral pictures ($p > 0.308$) and vice versa for negative pictures ($p > 0.160$).

Discussion

The results from this study show that participants could efficiently down-regulate their heart rate to both negative and neutral pictures when asked to do so. However, when viewing neutral pictures, participants could regulate their heart rate, whether the corresponding feedback was real or not. By comparison, when viewing negative pictures, participants clearly benefited from real feedback in that they could down-regulate their heart rate better, as compared to a condition when the feedback was fake. Ratings of task success were consistent with these results. Regulating heart rate to negative pictures while provided with real feedback was rated as more successful than when provided with fake feedback and interestingly, as equally successful as monitoring with real feedback. This suggests that receiving real online feedback about changes in heart rate facilitates the regulation of these specific physiological reactions while exposed to negative stimuli.

For neutral trials, participants rated being more successful when provided false feedback. This result was somewhat unexpected. This could paradoxically be explained by the mismatch between the actual feedback shown on the screen (hence being fake) and the participant’s expectations. Because neutral pictures did not lead to any detectable bodily reactions, the subjects may have relied on the external feedback information (rather than his/her actual bodily reactions) in order to judge whether he/she was successful. By contrast, in the real feedback condition, the participant may have (implicitly) detected some (weak) correspondence between his/her efforts to control his/her heart and the feedback shown on the screen. However, since neutral pictures were shown (and they yielded no clear change in bodily reactions), more efforts had presumably to be made by the participants in this condition, eventually leading to a lower perceived success in this condition (compared to the fake feedback condition).

The design in the current study included several control conditions. To control for effects of having a task to do while watching the pictures, we contrasted the heart rate regulation task to a control task. To control for effects of having biofeedback, we contrasted real accurate heart rate feedback to fake feedback. Also, to ascertain that participants showed directional emotional heart rate reactions when confronted to emotional pictures, we performed a contrast between emotional pictures and neutral pictures. Participants showed heart rate reactions to the negative pictures similar to those previously shown in the literature for emotional stimuli (i.e. larger initial deceleration followed by a larger acceleration, compared to neutral stimuli).

Participants also rated negative pictures as more arousing and more negatively valenced than neutral pictures. These results show that the negative pictures elicited differential heart rate effects and were rated differentially compared to the neutral pictures. Since the negative pictures were both more arousing and more negative than the neutral pictures, it remains unclear whether the reported heart rate effects were related to the first or second dimension. However, in real life situations, arousal and valence are rarely fully orthogonal. Our results therefore provide a first attempt to show the possible beneficial effects of online heart rate biofeedback during the regulation of negative emotion (here defined as a compound of negative valence and enhanced arousal). Another limitation of our study is related to the modest sample size, as well as the inclusion of female participants almost exclusively. Excluding the male participants did not change the main results, however.

The main finding showed that participants' heart rate regulation when viewing negative pictures was improved by the biofeedback. When viewing neutral pictures, heart rate regulation was not improved by the biofeedback. Because neutral pictures usually do not elicit reliable heart rate reactions, we did not predict a change in HR to these stimuli. However, we have to note that biofeedback has been shown to improve regulation of arousal in non-emotional situations (Blanchard & Young, 1973; Critchley, Melmed, Featherstone, Mathias & Dolan, 2002; Futterman, & Shapiro, 1986; Heffernan-Colman, Sharpley, King, 1992) suggesting that neutral pictures too might very well benefit from HR biofeedback. Our results do not support this alternative account though.

The subjective ratings of valence and arousal did not parallel the psychophysiological results, even though participants clearly judged negative pictures as more arousing and negatively valenced compared to neutral pictures. Neither task instructions, nor feedback type influenced subjective ratings. This dissociation suggests that despite an efficient "online" regulation of heart rate while viewing negative pictures (in particular when the feedback was real), it does not lead to a reduction in the perceived arousal or valence of the pictures, as measured using post-exposure ratings with discrete steps. Even though influential theories of emotion as well as more recent reviews would predict a close relationship between autonomic arousal and emotional experience (Critchley & Nagai, 2012; Damasio, 1994; Lang, 1994), the lack of corresponding changes in the subjective ratings post-exposure may tentatively be explained by several factors. Even though the instructions emphasized to rate the emotions experienced, while judging the arousal and valence of the picture, participants may have been biased by the obvious picture content overriding the subjective experience. Indeed, no differential effect of feedback type and task would be expected if participants primarily rated the (external) pictures, instead of their (internal) feelings. Alternatively, changes in heart rate depending on the feedback type, picture content, and task may have been too subtle to influence emotional feelings. Although biofeedback had an effect on participants' experience of task success, participants might not have experienced, at a conscious level, the phenomenology corresponding to the deceleration of the heart rate. We assume this because participants could judge task success by merely looking at the feedback information continuously shown on the screen. In this context, heart rate changes could have been too small to be consciously perceived, and hence appraised, precluding any effect at the level of the conscious emotional experience (Schachter & Singer, 1962). Finally, we also chose for post-exposure ratings (hence somehow based on a memory component), as opposed to dynamic ratings performed online during picture viewing, because the latter condition may have distracted participants away from the heart rate monitoring or regulating task. Presumably, single post-exposure ratings may be less sensitive than evaluation of subjective arousal and valence performed online, and being subject to moment to moment fluctuations (Nummenmaa, Glerean, Viinikainen, Jääskeläinen, Hari & Sams, 2012). At any rate, future studies are needed to establish whether the magnitude of biofeedback induced changes in heart rate (in particular accelerations) may predict corresponding changes in subjective feelings.

In the present study, inter-individual differences for the habitual emotion regulation strategies used by the participants did not influence the main findings. However, for future studies it might be interesting to see if the strategies used during the task influence the effect of biofeedback regulation. This could be done for example with a multilevel analysis enabling to disentangle the respective contribution of trait-related variables, used strategies and experimental factors (including the trustworthiness of the feedback information and the emotion content of the inducing stimulus or event).

The present results show that regulation with biofeedback influences the physiological component of a negative emotion. Importantly, they show that heart rate biofeedback was successfully used by participants in order to regulate the physiological component of an emotional reaction at a late stage, that is when the emotional reaction had already unfolded. It is well established that the most successful regulation strategies are started at an early stage and that there is a lack of emotion regulation strategies that are efficient to regulate negative emotions at a late stage (Gross, 1998; Gross, 2007). However, not all emotion reactions can be planned ahead and thus be regulated efficiently by means of an early or proactive emotion regulation strategy. In this context, heart rate biofeedback appears especially valuable, because it could provide an efficient way of regulating the physiological component of the emotion reaction at a late stage when the emotional reaction has already unfolded.

To summarize, the present study provides the first evidence that accurate online heart rate biofeedback provides a valuable way to efficiently down-regulate physiological reactions when encountering negative affect. Because unregulated physiological reactions may exacerbate anxiety, our findings might eventually be used to tailor new treatments or prevention strategies for anxiety disorders using continuous heart rate biofeedback.

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Figure 1: Each trial consisted of an instruction, fixation cross, picture presentation, and ratings of valence, arousal and task success. Ratings were performed on a 9-point scale showing arousal and valence figures from the Self-Assessment Manikin (SAM; Lang, 1980) and thumbs up/down.

Figure 2: Mean success ratings and heart rate responses (difference from baseline in bpm) to neutral and negative pictures for the four conditions (regulate with real feedback, regulate with fake feedback, monitor with real feedback, and monitor with fake feedback). Error bars represent standard errors of the mean (note that the error bars reflect between and not within subject variance and as such are non-informative for within subject statistical tests).

Figure 3: Time-course of heart rate to neutral and negative pictures, separately for the four conditions (for each time-point, mean heart rate is shown and computed as a difference relative to the pre-stimulus baseline; the vertical axis corresponds to picture onset). Note that the increase in heart rate in bin 1 corresponds to an anticipatory reaction when participants see the fixation cross.

Figure 1

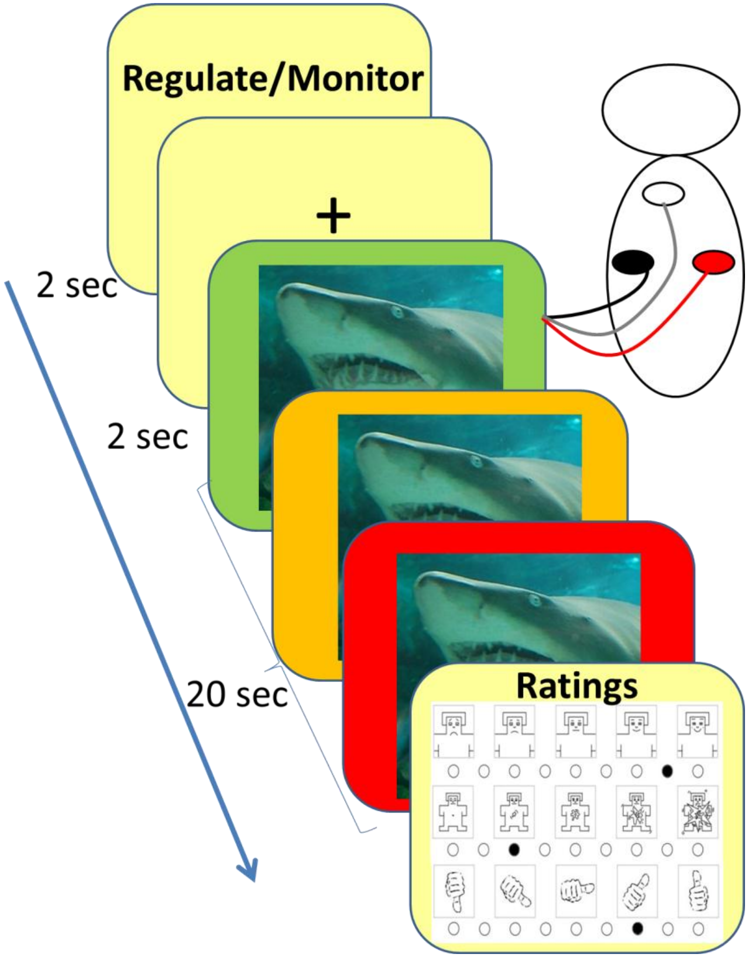


Figure 2

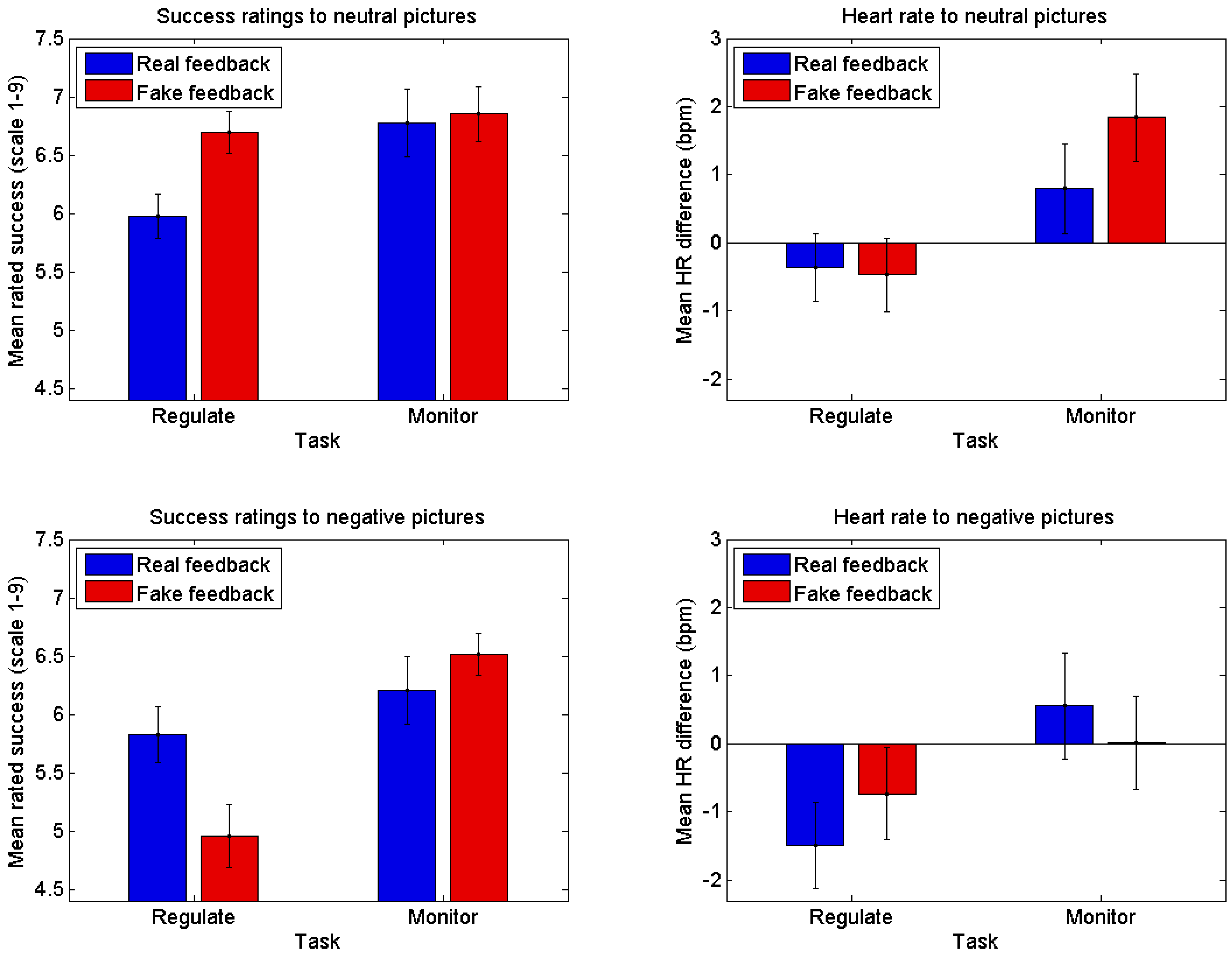
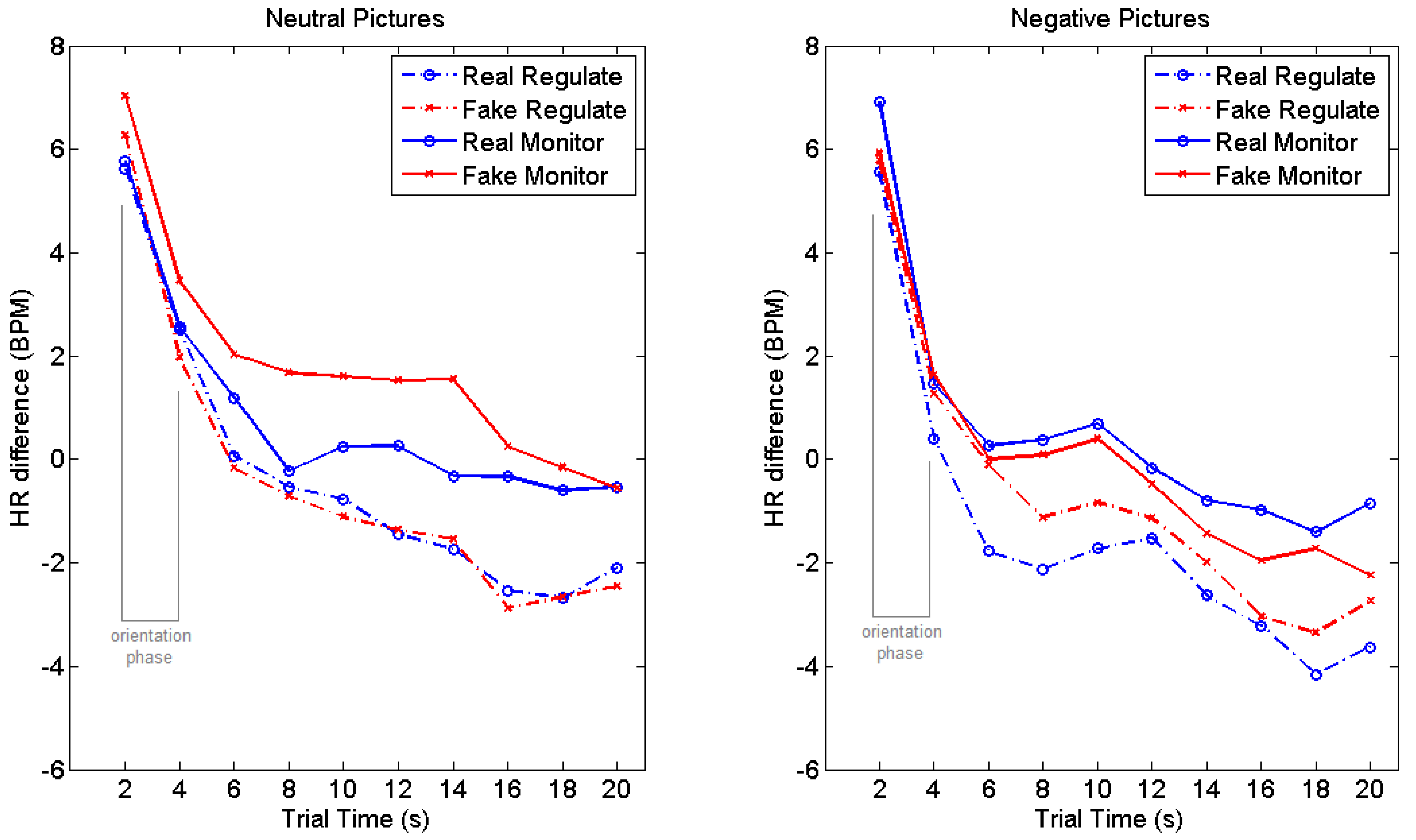

Success ratings to neutral pictures
Mean rated success (scale 1-9)
7.5
7
6.5
6
5.5
5
4.5
Real feedback
Fake feedback
Regulate
Monitor
Task
Heart rate to neutral pictures
Mean HR difference (bpm)
3
2
1
0
-1
-2
Real feedback
Fake feedback
Regulate
Monitor
Task
Success ratings to negative pictures
Mean rated success (scale 1-9)
7.5
7
6.5
6
5.5
5
4.5
Real feedback
Fake feedback
Regulate
Monitor
Task
Heart rate to negative pictures
Mean HR difference (bpm)
3
2
1
0
-1
-2
Real feedback
Fake feedback
Regulate
Monitor
Task

Figure 3


Neutral Pictures
Negative Pictures
HR difference (BPM)
Trial Time (s)
8
6
4
2
0
-2
-4
-6
2
4
6
8
10
12
14
16
18
20
Real Regulate
Fake Regulate
Real Monitor
Fake Monitor
orientation phase