Anger-based BCI Using fNIRS Neurofeedback

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ABSTRACT

Functional near-infrared spectroscopy (fNIRS) holds increasing potential for Brain-Computer Interfaces (BCI) due to its portability, ease of application, robustness to movement artifacts, and relatively low cost. The use of fNIRS to support the development of affective BCI has received comparatively less attention, despite the role played by the prefrontal cortex in affective control, and the appropriateness of fNIRS to measure prefrontal activity. We present an active, fNIRS-based neurofeedback (NF) interface, which uses differential changes in oxygenation between the left and right sides of the dorsolateral prefrontal cortex to operationalize BCI input. The system is activated by users generating a state of anger, which has been previously linked to increased left prefrontal asymmetry. We have incorporated this NF interface into an experimental platform adapted from a virtual 3D narrative, in which users can express anger at a virtual character perceived as evil, causing the character to disappear progressively. Eleven subjects used the system and were able to successfully perform NF despite minimal training. Extensive analysis confirms that success was associated with the intent to express anger. This has positive implications for the design of affective BCI based on prefrontal asymmetry.

Author Keywords

Brain-Computer Interface; Approach Motivation; Neurofeedback; Functional Near-Infrared Spectroscopy.

ACM Classification Keywords

H.5.2. Information interfaces and presentation: User Interfaces.

INTRODUCTION

The rapid progress of fNIRS applications to user interfaces makes it possible to envision a new generation of Brain-Computer Interfaces (BCI), with improved spatial resolution, better signal stability and greater robustness to motion artefacts [1, 40]. One particular interest for the development of BCI is the accessibility of specific prefrontal areas to fNIRS [11, 29, 43]. Ayaz et al. [5] have explicitly mentioned accessing signals from the dorsolateral prefrontal cortex (DL-PFC) in their application. This has important implications, as several anatomical areas of the DL-PFC are involved in executive functions [5] and emotional regulation [11, 22].

This could help addressing a persistent challenge for the design of affective BCI, which is to relate emotional processes to specific brain regions whose activity is accessible to measurement [19]. Prefrontal asymmetry is considered an important marker of affective-motivational state, in particular the approach/withdrawal[1] dimension [10], and has received considerable attention in clinical neuroscience. Its potential in the development of affective BCI has been recognized [28, 44] and has been the object of recent experiments [9], which exploited the original finding that asymmetry could be controlled by subjects through neurofeedback (NF) in clinical applications [35].

Zotev et al. [45] have conducted simultaneous EEG/fMRI experiments that confirmed prefrontal asymmetry as the anatomical substrate for approach and its variations during NF. Since fNIRS captures metabolic patterns similar to those observed in fMRI, this was a further encouragement to explore the use of fNIRS for prefrontal asymmetry NF.

One of the limitations of previous attempts at using prefrontal asymmetry as a measure of approach in BCI is the non-specific nature of its activation. Because approach is connected to appetitive stimuli [7, 34], it is not clearly dissociated from valence, and the expression of positive thoughts has been reported to induce prefrontal asymmetry. This was also described in Zotev's NF experiments [45], where the recollection of pleasant autobiographical memories was reported to induce prefrontal asymmetry. We observed similar phenomena in our previous EEG-based work on empathic BCI [12], where subjects' attitudes were split between expressing empathy and generic positive

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[1] *Approach* is related to the energization of behavior towards (positive) stimuli, whereas withdrawal (or avoidance) is related to directing behavior away from (negative) stimuli [10].
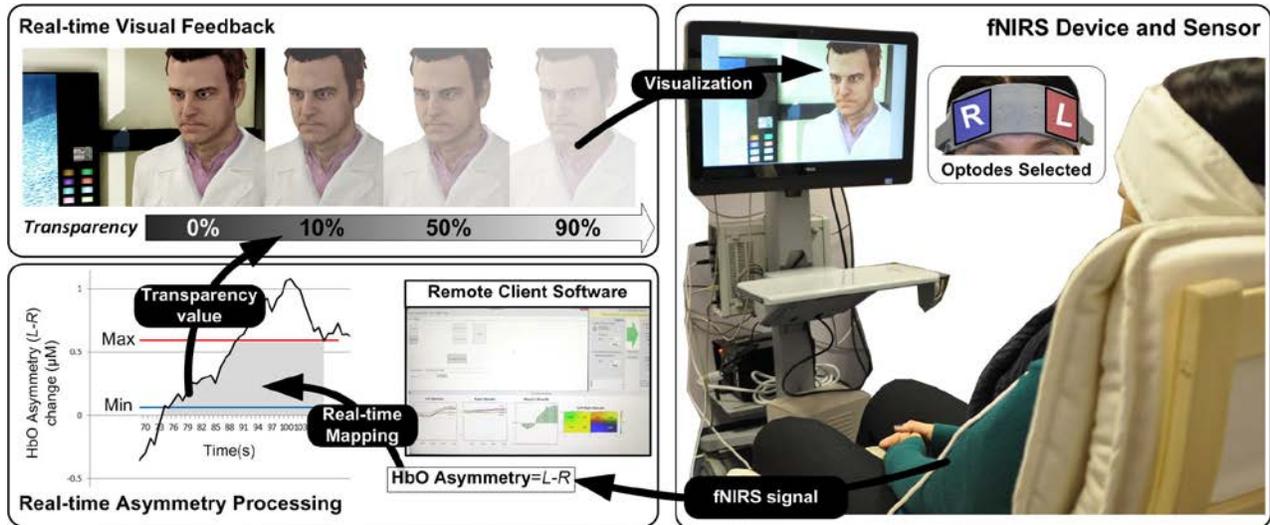
Figure 1. System Architecture. Input fNIRS signal is sampled at 2Hz and supports the calculation of a frontal asymmetry score. During NF, that score is linearly mapped to the visual appearance of a virtual character to reflect the expression of anger by the user; higher levels of prefrontal asymmetry result in the progressive disappearance of the character.

thoughts, sometimes autobiographical as well, hence unrelated to the visual NF target. However, for the future development of BCI based on approach/withdrawal, it is essential to establish that a specific approach signal can be produced independently of valence. Prefrontal asymmetry can be induced by positive thoughts only, some containing an approach component; however, Harmon-Jones [15] has established that in the case of anger, approach is clearly dissociated from valence: an anger response being characterized by increased left prefrontal asymmetry associated to negative valence (i.e. anger represents approach towards negatively perceived stimuli). A BCI strategy based primarily on anger would confirm the usability of approach for the design of affective BCI systems. In this paper, we describe such a system, in which users direct their anger at a virtual character.

PREVIOUS AND RELATED WORK

A significant fraction of previous fNIRS work has been dedicated to passive acquisition of user cognitive states [40], which has been used to assess cognitive workload [18], information presentation [32], or level of difficulty [13]. This has been applied to usability studies [17] and the development of adaptive interfaces [14], for instance through dynamic difficulty adjustment [2], recommender systems [31], or new pointing techniques [3].

However, our interest is instead in the use of fNIRS for active BCI, which has been introduced by Ayaz et al. [6] in the form of an fNIRS NF interface. The task given to users was to increase a bar value up to a certain predefined threshold: crossing the threshold defined NF success, and users' performance was further measured as the time required to cross the threshold. This design was later extended and incorporated to a more realistic environment

in the form of a 3D game [5]. Oum et al. [30] developed *MindTactics*, a 3D game environment incorporating fNIRS-based BCI, to experiment with BCI-based gameplay as well as supporting BCI research. User interaction is based on maintaining concentration, which is reflected through display bars, despite various distractors in the 3D environments.

The potential use of prefrontal asymmetry to support affective BCI has been discussed in various reviews [28], although without reporting specific implementations. Wehbe et al. [44] reported the use of EEG prefrontal asymmetry as a measure of arousal rather than approach, and applied this to user experience during game-based learning [44]. Karran et al. [21] explored the role of the PFC in subjects' aesthetic experiences using prefrontal asymmetry as a measure of valence. In our previous work [12], we explored the use of EEG alpha prefrontal asymmetry NF to implement affective BCI input to an interactive narrative. In this system, users would express positive empathy towards a 3D virtual character, resulting in a more favorable evolution of the story. Data acquired from simultaneous fMRI analysis of the PFC was consistent with the original hypothesis but could not be interpreted further, in view of the small number of subjects.

SYSTEM OVERVIEW

We designed a NF system around commercial fNIRS equipment. The overall architecture of the system is presented on Figure 1. Our system computes real-time variations of prefrontal asymmetry from the acquisition of hemodynamic data and produces visual feedback to the user, based on the rendering and animation features of a 3D game engine (UDK™).

Figure 2. User attitudes towards the target character are prompted by showing user excerpts from the background narrative, portraying him as mischievous.

The scenario for the anger-based interface consists for the user to express anger against a virtual character. Throughout specific NF epochs, users actively express anger towards the character: in return, based on their variation in prefrontal asymmetry, the character's images fades from the environment, as if they had the ability to erase him. Like with most NF systems, the core calculation consists in the real-time mapping between the neural signal (here prefrontal asymmetry) and the visual feedback signal (image transparency for the virtual character).

We developed experimental software which automates protocol timing, data collection, stimulus presentation, as well as embedding the NF module. Remote client software connected to the data collection software manages the real-time processing of values of oxygenated hemoglobin (HbO) concentration changes, the triggering of baseline capture, as well as sending marker information for post-processing of fNIRS data. The metric of inter-hemispheric difference in the level of HbO change is calculated in real-time as the difference of the four leftmost and four rightmost channels (i.e., asymmetry = L-R, [11]). The graphical user interface (Figure 1), developed using C# and Windows WPF, includes a real-time visualization of HbO changes and asymmetry values. All these variables are logged during the experiment to facilitate the post-processing of the collected data. This graphical user interface was also used to manage the running of the experiment itself, which included displaying the required epochs (text, image, video, or more complex visualization) and managing their duration and the synchronization of all the software components. Finally, this interface was also used to implement visual feedback.

In the next sections, we describe our experimental design and give details on the real-time aspects of NF implementation; we also present global success criteria for a neurofeedback epoch. We then analyze experimental results to evaluate BCI performance.

METHODS

Subjects
Twelve adults were recruited at the authors' institution. One subject had to be excluded due to technical problems, which left an effective sample size of 11 (mean age = 33.55 years, SD = 11.53, range: [24; 59], 5 female). Subjects had no history of psychiatric conditions and were right-handed.

They all provided written consent prior to participation. The experiment was approved by a research ethics committee at the authors' institution. Each subject was compensated with an online retailer voucher equivalent to $30.

Apparatus
We used an fNIR Optical Brain Imaging System (fNIR400) by Biopac Systems for data acquisition. Raw fNIRS data and oxygenation values were collected with 2Hz sampling rate (using COBI Studio and FnirSoft v3.5), and was sent to the experimental software over TCP/IP (using FnirSoft DAQ Tools). A 16-channel sensor with a fixed 2.5cm source-detector separation was placed on the subjects' forehead. For real-time application we used measurements of changes in HbO concentration, as opposed to deoxygenated or total hemoglobin (HbR and HbT, respectively), because it has been reported to be sensitive to task-related activation in the PFC [3] and to affect-related experimental manipulation in the DL-PFC [43], and it has been successfully applied in research involving approach/withdrawal-related manipulation [27]. Values of HbO concentration changes were averaged over four leftmost and four rightmost channels[2] (located over the left and right DL-PFC, respectively) to derive a simple metric of inter-hemispheric difference in the level of HbO change (see [11]) that could account for left prefrontal asymmetry.

We followed the recommendations of Solovey et al. [39] regarding the use of fNIRS in a HCI setting. Subjects were seated approximately 47" (120cm) from a 24" flat monitor in a dimly-lit, quiet (but not soundproof) room in a comfortable chair to minimize movements, with the fNIRS probe positioned over their forehead and covered with non-transparent fabric to prevent ambient light reaching the sensors (see Figure 1). Subjects were instructed to refrain from moving their limbs, frowning and talking during data-collection blocks indicated by the experimental software.

Subjects Instructions and Questionnaires
To set a context for the NF task involving anger expression, subjects watched 3D animations from a narrative set in a hospital environment, comprising four short scenes (overall length: 71s) illustrated in Figure 2. The objective of these scenes was to introduce the target character as a despicable subject, one at which it would be appropriate to target anger. The background narrative is a medical drama, in which the character features as unethical and as a bully. In the first scene, he is shown sexually harassing a female colleague. In other scenes, he belittles colleagues and ridicules their professional abilities, or he boasts about getting away with professional malpractice. To assess the effectiveness of setting the context, we asked subjects to

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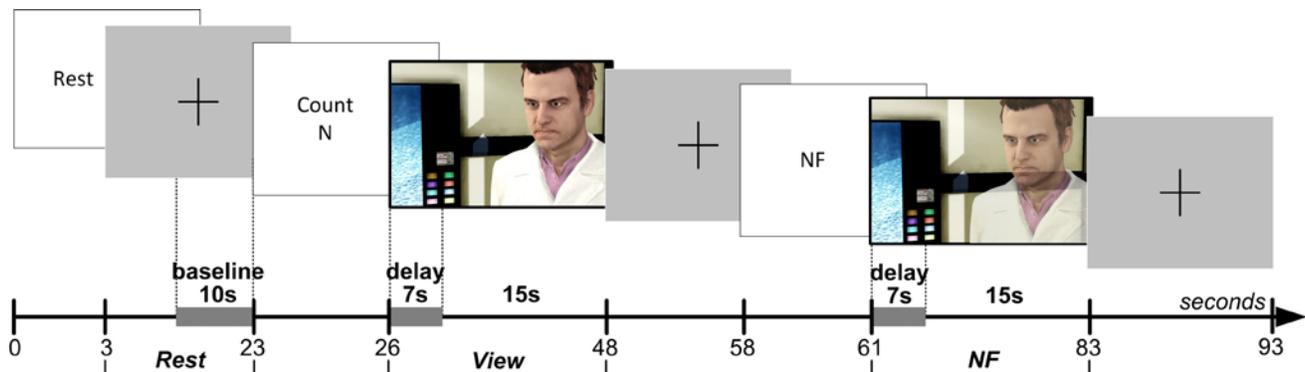[2] See [33] for a similar approach to combining specific channels to form a single measure.

Figure 3. Block Design. The main three epochs of the block are a Rest epoch, a View epoch, and an NF epoch (all 3 epochs were preceded by a 3s prompt to count). View epochs are used to provide a reference for the following NF epoch, also controlling for visual stimulus to avoid artifacts due to spontaneous affective response.

rate the seriousness of the presented case of bullying on a 1 to 10 scale. The smallest seriousness rating was 7 (M = 8.36, SD = 0.95, range: [7; 10]), indicating that the clip set an adequate context for expressing anger towards the target character (i.e. the male doctor or 'the bully').

Since the experiment involved expressing anger towards a virtual agent, we included in the protocol the psychometric measurement of anger using the State-Trait Anger Expression Inventory (STAXI-2; [41]) to assess the relationship between anger disposition and NF success through the expression of anger. Subjects completed the 10-item trait scale of STAXI-2 to assess their disposition to perceive certain situations as annoying or frustrating, and their tendency to respond to such situations with elevated state anger.

Next, subjects were instructed that they would go through a sequence of blocks, each comprising three main epochs: *Rest*, *View* and *NF* (see Figure 3). During *Rest*, the baseline for calculating HbO data is acquired for the block as a whole. The *View* epochs correspond to control conditions, during which the subjects watch an idle animation of the character while given a cognitive task (counting, see [29]) that keeps them in a neutral state, hence providing a reference for prefrontal asymmetry levels. Finally, the *NF* epochs consist in subjects expressing anger towards the character and receiving visual feedback. Subjects were instructed to express their anger "mentally" and did not receive specific instructions that could bias their cognitive strategy. They were simply reminded that their anger had to be targeted at the character.

Each subject completed two training blocks to get acquainted to the task, followed by six blocks for the experiment itself, during which HbO asymmetry was monitored and recorded. After each block, subjects rated the amount of anger they felt they managed to express

towards the target character on a 1 to 10 scale. They were then also asked to describe their cognitive strategy in expressing anger during the block.

Block Structure: View and Neurofeedback Epochs
Each block started with a verbal prompt to rest (lasting 3s) presented in the center of a grey screen. The prompt was replaced by a crosshair that remained on screen for 20s. The subject was instructed to keep looking at the center of the screen and relax. The last 10s of the *Rest* epoch (20 observations sampled at 2Hz) was used to calculate the baseline for the block as a whole (see [36]).

The *View* epoch started with a written prompt to count and a single-digit integer. The task was to count backwards from 500 by subtracting the provided integer. After 3s, the prompt was replaced with an idle video of the target character (the "bully") that remained on screen for 22s. The subject was instructed to keep looking at the screen and carry on doing the counting task in her head until the character was replaced by a crosshair. It was followed by a 10s between-epoch interval, during which the crosshair was displayed again on a gray background, and the subject was instructed to abandon the counting task and relax.

The *NF* epoch started with a written prompt to express anger. After 3s, the prompt was replaced by a still shot from the idle video the subject was previously shown during *View*; this picture was used as the feedback channel. The subject was instructed to keep looking at the screen while expressing her anger mentally towards the target character, and that she can make the picture of the character fade away from the surroundings if she expressed anger effectively. The scene was replaced by the crosshair after 22s. No behavioral expression of anger (such as marked facial expressions) was observed for the vast majority of users during experiments. Each block was finished with the crosshair presented at the center of a grey screen for 10s.
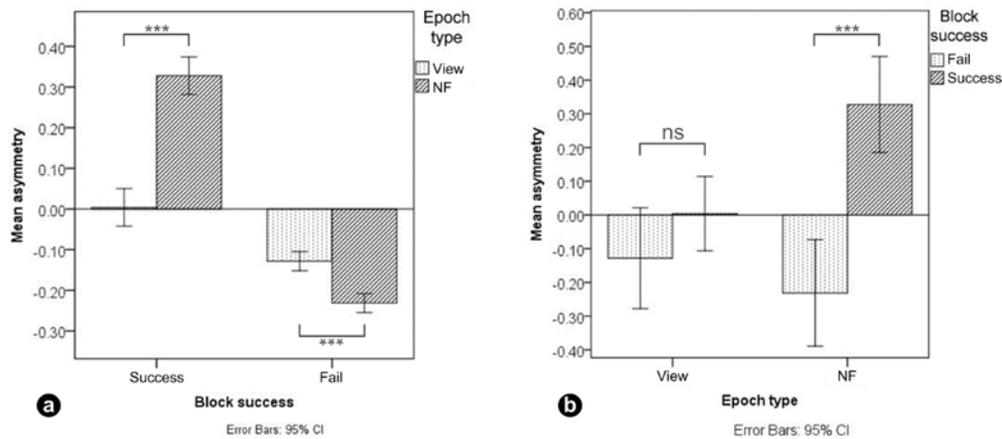
Figure 4: Differences in asymmetry in successive *View* and *NF* epochs. (a) Comparisons across epoch type (within-subject factor; note that the error bars are based on within-block variance between successive *View* and *NF* epochs). (b) Comparisons across block success (between-subject factor): asymmetry in View epochs did not differ significantly across levels of block success, confirming that success was primarily due to an increase in left-side activation during *NF* blocks.

It should be noted that, rather than inducing anger in subjects through experimental manipulation (e.g., [16]), we asked them to generate a state of anger towards a target. This was for the purpose of using anger as voluntary affective input through fNIRS, rather than attempting to detect induced anger with this method.

Neurofeedback Success Criteria
Although subjects get an indication of success through visual feedback, there is a need to objectively assess success over an entire block, as well as quantifying it for further analysis. fNIRS signals are relative to a baseline [4] and it can be difficult to compare them across subjects [37]. Moreover, the magnitude of oxygenation changes can also differ substantially across blocks within the same subject. Therefore, we designed our success criterion for defining and quantifying block success to mitigate the issue of comparability.

As discussed above, we used the last 10 seconds of the *Rest* epoch at the start of each block to calculate the baseline for the block [36]. Since we characterized asymmetry as the difference between average HbO changes in the left and right DL-PFC, asymmetry during baseline was defined as zero. This operationalization of asymmetry yielded interval-level data (values had no meaningful absolute zero point). Consequently, we could not use a ratio of task/no-task signals for defining and quantifying success, and providing feedback (e.g., Sarkheil et al. [38]).

As a solution, we treated a block as successful if the mean of asymmetry values during the *NF* epoch was statistically significantly larger than the mean of asymmetry values during the *View* epoch within the same block. As opposed to simply comparing asymmetry scores during *NF* to the overall baseline, we compared asymmetry scores between the successive *View* and *NF* epochs because the visual stimulus was very similar (and conceptually the same) in the two epochs. Moreover, we set conditions for controlling subjects' cognitive activity during these epochs (counting during *View* and expressing anger during *NF*), whereas thought processes during *Rest* were not controlled. Thus, the *View* epoch served as a control condition within each block.

Because the hemodynamic response measured by fNIRS occurs in approximately 7s [8], we discarded the first 7s of data in each *View* and *NF* epoch for determining block success. The system determined block success by performing and independent t-test on the set of asymmetry scores collected during successive *View* and *NF* epochs within a block. In particular, it calculated mean and standard deviation (SD) of asymmetry scores in both epochs, and then calculated the t value. Since removing the first 7s left 15s of data per epoch (at least 29 data points sampled at 2Hz), the software used the t critical value of 2.05 with 28 degrees of freedom for p (two-tailed) = .05 as a threshold for success. Furthermore, to quantify the extent of block success by expressing the distance of the distribution of asymmetry scores during successive *View* and *NF* epochs, the experimental software calculated the Cohen's d effect-size measure, which is the difference between two means divided by the pooled standard deviation. This way we characterized each block with a dichotomous success value (success/fail) and a continuous success score (Cohen's d or d for short) that reflects the distance between the distribution of asymmetry values between *View* and *NF* epochs within the same block.

Real-time Neurofeedback Mapping
Mapping is an essential part of any NF software, as it ensures that the individual variations in target neural activity are consistently translated into variations of the feedback signal. In the present case, this involves determining the individual range of variation of HbO asymmetry and establishing a mapping function between
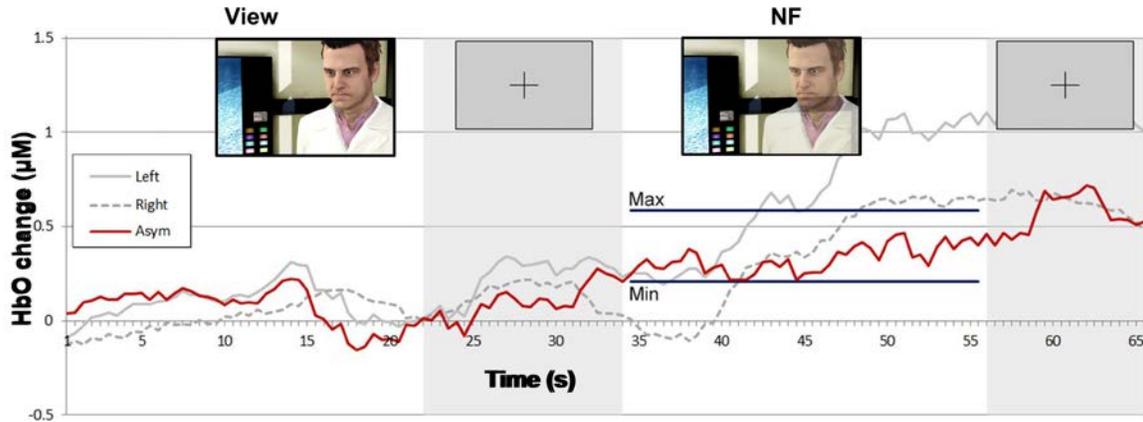
Figure 5. Example of asymmetry variation over time in a successful block. The horizontal lines in the *NF* epoch (labelled Min and Max) represent the range of values which determines NF mapping. Note that during the *NF* epoch, HbO increases bilaterally, with a marked asymmetry to the left.

asymmetry values in that range and the 0-100% variation of the visual signal (image transparency, see Figure 1). Within each block, we used the asymmetry scores during the *View* epoch to determine the range for mapping asymmetry values to the feedback channel during the *NF* epoch. This was calculated by the system during the between-epoch interval, to automatically parameterize mapping during *NF*.

We defined the minimum point for mapping (Min) as the mean of asymmetry values during *View* plus 1.28 times their SD (the asymmetry value for which the visual feedback is equal to 10% transparency). Assuming normally distributed asymmetry scores, this threshold would result in no feedback for 90% of the spontaneous asymmetry variations during *View*. This approach to the determination of NF threshold for left-asymmetry is consistent with the original one of Rosenfeld et al. [35] for EEG. To determine the (Max) value of asymmetry, resulting in maximum visual feedback (i.e. 100% transparency), we increased the threshold for feedback (Min) by the maximum variation range of asymmetry during *View*.

The feedback range thus determined during the *View* epoch immediately preceding *NF*, mapping can take place in real-time between asymmetry values collected during *NF* and the visual transparency of the target character over the background (Figure 1). The camera location and angle within the 3D scene were generated identical to the *View* epoch's visualization, and the target character's image was overlaid on top of the 3D scene background image. Asymmetry values within the range [Min; Max] were mapped linearly onto the visual transparency range of 0-100% (Figure 1), with the same 2Hz frequency as the acquisition of asymmetry values. For real-time updating, asymmetry values reaching the feedback threshold (Min) were mapped by 10% increments in transparency, while values reaching (and exceeding) the maximum (Max) were mapped to 100% transparency.

RESULTS AND ANALYSIS

Block Success

We defined block success as a statistically significant increase in average asymmetry during the *NF* epoch compared to the *View* epoch within the same block. Out of the total 66 blocks collected from the 11 subjects, 38 were successful (58%). Eight out of 11 subjects (73%) completed at least half of the blocks successfully (Median = 4 blocks out of 6)[3]. One subject had no successful blocks; no subject completed all blocks successfully. We complemented the dichotomous success criterion with a continuous success score, characterized with the Cohen's d effect-size measure. Mean score in successful blocks was d = 2.39 (SD = 1.56), which corresponds to an average 23% overlap in asymmetry scores between *View* and *NF* (assuming normally distributed asymmetry values). The smallest effect size we could detect (in 15s of asymmetry data sampled at 2Hz, with a two-tailed p < .05 criterion) was d = 0.59 (medium), which corresponds to a 76% overlap between asymmetry values during successive *View* and *NF* epochs. This indicates that our success criterion was sensitive to detect relatively small increases in asymmetry, while asymmetry values in most successful blocks had small overlap between *View* and *NF*.

To determine if observed effects were indeed related to users' intentional behavior, subjects rated the amount of anger they expressed towards the target character during the *NF* after each block on a 1 to 10 scale. In successful blocks, the self-reported magnitude of expressed anger was significantly correlated with the success score, r = .33, p = .043. Conversely, the magnitude of expressed anger was uncorrelated with the success score in failed blocks,

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[3] See [9], and also [35] for a similar way of defining NF success at subject level.
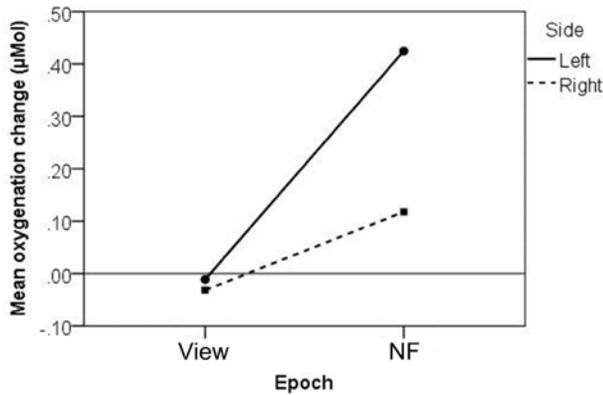
Figure 6: Differential increase in left-side oxygenation in successful blocks.
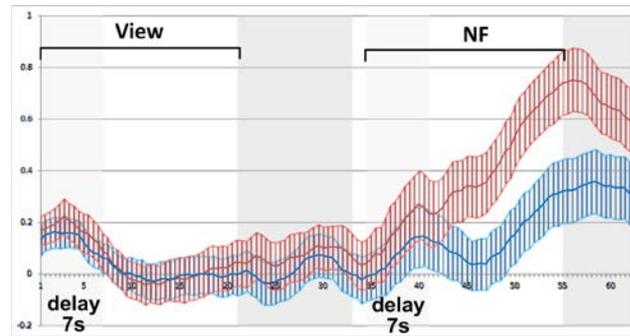

Figure 7. Mean and standard error of fNIRS signal (HbO) across all successful blocks (n=38) for left (Red) and right (Blue) sides separately. Note that the signal overlaps on the two sides during *View*, while left rises above right during *NF*.

r = -.07, p = .725, ns. In addition, the self-reported magnitude of expressed anger during *NF* was uncorrelated with STAXI-2 trait and state scales. However, the temperament subscale of the STAXI-2 trait scale was significantly correlated with the success score, r = .27, p = .026, which suggests that people with higher dispositional trait anger may be more effective in up-regulating frontal asymmetry by mentally expressing anger towards a target.

Asymmetry across *View* and *Neurofeedback* Epochs

Another validation of the interface consists in confirming that spontaneous fluctuations of asymmetry cannot account for the observed effects. To that effect, we explored changes in asymmetry between *View* and *NF* epochs in relation to blocks success with a 2 x 2 Mixed ANOVA. Note that the significant interaction effect between success and epoch type (F(1, 64) = 56.78, p < .001) is trivial, since we defined block success with significantly larger asymmetry during *NF* than during *View*. We therefore concentrate on post-hoc pairwise comparisons (see Figure 4). In successful blocks, average asymmetry during *View* was zero (M = 0.00, SD = 0.34), while average asymmetry during *NF* (M = 0.33, SD = 0.43) was significantly larger, t(37) = 7.10, p < .001, r = .76 (large). Conversely, failed blocks where characterized with a decrease in asymmetry between *View* and *NF*, t(27) = -4.54, p < .001, r = .66 (large).

Additionally, asymmetry during *View* did not differ significantly in successful (M = 0.00, SD = 0.34) and failed (M = -0.13, SD = 0.39) blocks, t(64) = 1.48, p = .143, ns, r = .18 (small), while asymmetry during *NF* was significantly larger in successful blocks (M = 0.33, SD = 0.43) than in non-successful ones (M = -0.21, SD = 0.41), t(64) = 5.31, p < .001, r = .55 (large). These findings indicate that successful and non-successful blocks differed predominantly on the basis of increase in asymmetry during *NF*, as opposed to lower levels of asymmetry during *View*. This confirms the role of active expression of anger over baseline fluctuations (Figure 5).

Lateralized Difference in Activation across *View* and *Neurofeedback* Epochs

To explore how oxygenation changes on both sides contributed to the increase in asymmetry from *View* to *NF* within successful blocks, we conducted a 2 x 2 mixed ANOVA on average oxygenation changes with Epoch (*View*/*NF*) as within-subject factor and Side (Left/Right) as between-subject factor. The analysis revealed a significant interaction, F(1, 74) = 7.86, p = .006, partial η^2 = .10, which indicates that oxygenation changed differentially on the left and right sides between consecutive *View* and *NF* epochs (see Figure 6). Conducting the same analysis for failed blocks revealed no significant interaction, F(1, 54) = 0.16, p = .688, ns, which indicates no differential change in oxygenation from *View* to *NF* in failed blocks. We conducted post-hoc pairwise comparisons to break down the significant interaction effect. In successful blocks (Figure 6), on the left side, average oxygenation increase from *View* (M = -0.01, SD = 0.44) to *NF* (M = 0.42, SD = 0.61) was statistically significant, t(37) = 6.20, p < .001, r = .71 (large). On the right side, average oxygenation increase from *View* (M = -0.03, SD = 0.39) to *NF* (M = 0.12, SD = 0.62) approached significance, t(37) = 2.01, p = .051, r = .31 (medium). Note that the magnitude and effect-size of oxygenation increase was markedly larger on the left side. These findings indicate that although oxygenation increased on both sides during *NF* in successful blocks, asymmetry was predominantly a result of differential increase in left-side oxygenation (Figure 7). Conversely, post-hoc pairwise comparisons conducted on non-successful blocks revealed no significant change in oxygenation between *View* and *NF* on either side (Left: t(27) = 0.39, p = .703; Right: t(27) = .98, p = .335). Additionally, STAXI-2 trait anger was significantly correlated with the magnitude of left-asymmetry during *NF*, r = .33, p < .01, which is consistent with the findings of Harmon-Jones [15]. Specifically, the temperament subscale of trait anger was significantly and positively correlated with left-side activation increase during *NF* epochs, r = .27,

p = .03, while it was uncorrelated with right-side activation, r = .01, p = .96, ns.

Cognitive Strategies for Expressing Anger

For most users, the unusual experience of controlling brain areas activation through NF requires them to adopt a cognitive strategy, *i.e.*, a set of thought contents on which to concentrate during NF epochs. Cognitive strategies are known to constitute an important aspect of NF systems [25], including those based on fNIRS [5]. After completing each block, subjects were thus asked to describe their strategy for expressing anger towards the target character during *NF*. Subjects' anger-expression strategy predominantly comprised of imagining being part of the scene and confronting the target character either verbally (e.g., rebuke and shouting), physically (e.g., pushing the target character or beating him up), or a combination of the two. These strategies were used in nearly 80% of all blocks, each subject applied them and, with the exception of a single subject with no successful blocks, everybody succeeded with them at least once. Moreover, each subject tried one of these simple strategies out first: 4 subjects applied a verbal strategy during their first block, 2 applied physical, and 5 applied a combined verbal-physical. The most successful strategy was physical only, which worked 75% of the time it was applied, followed by a combination of verbal and physical (48% success rate) and verbal only (36% success). This confirms that subjects were able to elicit natural cognitive strategies for anger despite minimal instructions, with a clear indication that some of the most successful ones included an approach component.

Results Interpretation

The above results confirm that when instructed to express anger, subjects show increased levels of left prefrontal asymmetry [16]. We have considered alternative explanations for the observed physiological response, but these are not supported by our experimental data. The effect of concentration alone cannot explain the observed asymmetry, as subjects rated the counting task as mentally difficult as the NF task, suggesting similar concentration levels. Wilcoxon signed-rank test revealed no statistically significant difference in subjective difficulty between Count (M = 5.41, SD = 1.45) and Anger (M = 6.91, SD = 2.26) tasks rated on a 10-point scale, T = 15, z = -1.608, p = .11.

Negative thoughts towards the character cannot explain the observed asymmetry, as PFC asymmetry is not induced by negative valence [7]. Finally, a form of preoccupation for the victim character, known as *concern empathy* [24], would actually decrease, rather than increase, left PFC asymmetry [24]. Furthermore, if we consider that successful subjects reported high levels of expressed anger, and the magnitude of left asymmetry during NF was significantly correlated with STAXI-2 trait anger, we can conclude that experimental results are compatible with our initial hypothesis.

An overall success for 73% of first-time users with minimal training is consistent with the state-of-the-art in fNIRS-based BCI [19]. It should be noted that typical NF experiments (in clinical research) include extensive training spread over multiple sessions: for instance, Rosenfeld et al. [35] reported training subjects over three days prior to NF experiments, and Kotchoubey et al. [23] up to eight weeks. These results, together with accepted figures of BCI illiteracy of around 20%, are encouraging in terms of future usability of the system. In addition, 7 subjects (64%) succeeded within the first two blocks (4 of whom succeeded in both blocks).

Perspectives for User Interface development

The ability to control approach as an affective dimension possesses an important potential for user interaction, which is only beginning to be explored. Firstly, approach is related to motivational processes, which is an important element of a user state to capture, in particular when its value can be controlled over a continuous range. Secondly, approach naturally relates to a specific target, which can be made an explicit element of the interface layout (e.g., a virtual agent in a narrative, and a landmark or a destination in a map). The experiment we presented suggests that approach can be selectively controlled independently of valence, which is an important confirmation for its use in interactive systems. The actual use of approach in user interfaces can be subject to various design decisions depending on the nature of the application. For instance, some systems may only use approach in a positive valence context, while other may actually use anger itself (in training or entertainment applications). Systems that would rely on the use of approach in both contexts may require an additional channel capturing valence, although the context itself could also provide disambiguation.

CONCLUSIONS

We have shown that fNIRS could support the implementation of an active, affective BCI based on approach, under a NF paradigm. Subjects were able to successfully use the interface with minimal training, and BCI results were correlated with self-reported anger. Compared with previous work based on EEG prefrontal asymmetry [9], our approach harnesses the standard benefits of fNIRS [17, 29], in terms of spatial resolution (in particular in the prefrontal area) and greater signal stability. An advantage of our system is that it relies on relatively simple calculations and does not require complex online categorization algorithms. Our results can inform the design of affective BCI associated with prefrontal asymmetry, which is involved in a wide range of user mental states, from empathy to anger, or even risk-taking.

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