Evaluation of emotional and neutral pictures as flashing stimuli using a P300 brain-computer interface speller

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Abstract

Previous works have reported that complex emotional and visual stimuli can increase the amplitude of the P300 brain potential. Thus, the aim of the present work is to assess these kinds of images in a P300 brain-computer interface speller as flashing stimuli. Twenty-three volunteers controlled four spellers with different sets of flashing stimuli: flashing letters (FL), neutral pictures (NP), emotional pleasant pictures (EPP) and emotional unpleasant pictures (EUP). The sets of pictures showed a higher performance than the letters in accuracy and information transfer rate. These results were supported by the analysis of the P300 signal, where the picture sets offered the greatest amplitudes. The NP and EPP sets were the best evaluated in the subjective questionnaire. In short, despite the fact that the effect of emotional stimuli could not be observed in the performance metrics, picture sets have offered a high performance and should be considered in future proposals.

Keywords: brain computer-interface (BCI), event-related potential (ERP), speller, stimulus, picture, emotion

1. Introduction

The term 'brain-computer interface' (BCI) includes a group of systems that offers the possibility of setting a communication channel between a user and a device just through his/her brain signal (Jonathan R. Wolpaw, Birbaumer, McFarland, Pfurtscheller, & Vaughan, 2002). This technology may be a convenient option for those patients with motor abilities severely affected by some motor neuron diseases, such as amyotrophic lateral sclerosis (ALS) (Patterson & Grabois, 1986).

Most of these interfaces use electroencephalography (EEG) as a method to record the brain signal due to its adequate temporal resolution, portability and relative low cost (Nicolas-Alonso & Gomez-Gil, 2012). More specifically, the P300 is a positive deflection in the voltage of the EEG signal, generally registered from the parietal lobe of the cortex, around 300 ms after the presentation of an uncommon target stimulus. According to Nicolas-Alonso & Gomez-Gil (2012), the main advantages of the P300-based systems are: i) they do not require extensive training for management, only a small calibration to adjust the system settings to each user's brain activity; ii) they tend to have high success rates and iii) they allow a high number of options to be chosen by the participant.

The most widely studied BCI application could be the P300-based spellers since the publication of Farwell & Donchin (1988). This classic speller consisted of a 6 × 6 matrix of letters and numbers, whose rows and columns were briefly intensified (i.e., flashed) a given number of times in a random order. Thus, the user just had to keep his/her attention over the target character and mentally count the number of times that it was flashed. As this character was presented in one specific row and column, the P300 can be used to find the target stimulus using the oddball paradigm. Once a sequence of flashes was over, the symbol that belonged to the row and column that had produced the largest P300 was regarded as the attended character and given as feedback to the user. Following the paradigm presented by Farwell & Donchin (1988), numerous variations have been proposed to improve the use of a P300 speller matrix. Some research has focused on certain parameters such as: variations in the lighting patterns (Townsend et al., 2010), the presentation times and brightness intensity (Li, Bahn, Nam & Lee, 2014), the size of the stimuli and the distance between them (Li, Nam, Shadden & Johnson, 2011), the colour (Takano, Komatsu, Hata, Nakajima & Kansaku, 2009), the number of stimuli (Sellers, Krusienski, McFarland, Vaughan & Wolpaw, 2006) or even their nature, i.e., letters, faces or geometrical figures (Kaufmann et al., 2011). Our study concentrates on the last topic: studying what type of stimuli could be used to improve the performance when controlling a BCI speller.

In early potentials (i.e., those that occur before 300 ms after the appearance of a stimulus) a categorisation of the nature of the stimulus is produced, mainly due to the physical characteristics (Pratt, 2012). Currently, the stimuli that have shown an improvement on the BCI speller performance are the familiar faces, which produce an increase in the N170 potential (Kaufmann et al., 2011). However, this familiar faces paradigm (FFP) was improved by Li, Liu, Li & Bai (2015) by using a small modification: they changed the colour of the faces to green, giving rise to the green familiar face paradigm (GFFP). The green colour has been associated with relatively high levels of arousal and valence (Valdez & Mehrabian, 1994). Moreover, higher arousal stimuli produced larger amplitudes in this brain signal (Cuthbert, Schupp, Bradley, Birbaumer & Lang, 2000; Rozenkrants & Polich, 2008). Thus, Li et al. (2015) suggested that the increase in the amplitude of the ERP waveform may be produced by the green colour. Likewise, it has been demonstrated that the use of stimuli with greater stimulating complexity can evoke a greater amplitude in early ERP components and, thus, improve the user performance controlling a P300 speller (Ma & Qiu, 2017).

As a consequence of these previous findings, it could be interesting to study the use of complex pictures by considering the properties of valence and arousal. Thus, a standardized set of pictures (in terms of valence and arousal) could be used, such as the International Affective Picture System (IAPS) (Lang, Bradle, & Cuthbert, 2008)). Outside the scope of the BCI, the pictures of the IAPS have been used in numerous works to study the modulation of the event-related potential (ERP) signal due to the emotional properties of the presented stimuli (see the reviews of (Olofsson, Nordin, Sequeira & Polich, 2008) and (Hajcak, Macnamara & Olvet, 2010) for a more exhaustive exploration of the topic).

In the review of Hajcak et al. (2010), it was declared that most studies in emotion have been focused on the previously mentioned P300 and the late positive potential (LPP). The LPP is a midline ERP whose maximum amplitude is located between 500 and 800 ms after a stimulus onset and it is amplified by the presentation of pleasant or unpleasant pictures, compared to neutral pictures and words (Cuthbert et al., 2000; Garrison, Crowell, Finley & Schmeichel, 2017; Rozenkrants & Polich, 2008). Moreover, the LPP evoked by emotional pictures, compared to that evoked by neutral pictures, has shown a larger amplitude with more intense stimuli (i.e., those rated as being more arousing) and, specifically, with higher pleasant and unpleasant arousal stimuli, such as erotic and threatening scenes, respectively (Cuthbert et al., 2000; Rozenkrants & Polich, 2008; Schupp, Junghöfer, Weike & Hamm, 2004). Additionally, the effect provoked by emotional stimuli in the LPP remains, even when using a relatively small stimulus size (5 × 4 cm at a 100 cm distance from the screen, i.e., 2.68º × 2.05º of visual angle) (De Cesarei & Codispoti, 2006) and in a rapid serial visual presentation (Schupp et al., 2004), so this effect might be maintained using a standard row-column presentation in a BCI speller matrix.

According to the previous paragraphs, it is possible that pictures (comparison to white letters) produce: i) an increase of amplitude of the early potentials (P1, N1, P2, N2) due to the greater complexity of the stimulus and ii) an increase of amplitude of the late potentials (P300 and LPP) due to their emotional properties. Therefore, the aim of this work will be to study i) whether a P300 BCI speller paradigm based on pictures can improve performance versus a standard grey-to-white letter paradigm and, ii) whether there are differences between a paradigm based on emotional pictures and others based on neutral ones. We are aware that extreme excitatory and emotional pictures (such as explicit nude women or a mutilation) will be shown, so this proposal might not be suitable for general usage (i.e., in social environments). However, we believe that it is important to delimit this problem, i.e., to test if an emotional paradigm could improve performance and, if so, to adapt future studies in terms of the degree of both dimensions, considering user satisfaction.

2. Methods

2.1 Participants

The study initially involved 23 heterosexual participants (aged 24.52 ± 5.31, 11 females) who had normal or corrected-to-normal vision, identified as E1 to E23. None of them had previous experience of BCI systems. The subjects were recruited through the use of social networks and posters around the campus of the University of Malaga. The study was approved by the Ethics Committee of the University of Malaga and met the ethical standards of the Helsinki Declaration. According to self-reports, none of the participants had any history of neurological or psychiatric illness. Participants received monetary remuneration of 10 € and all of them provided written consent.

2.2 Data acquisition and signal processing

The EEG was recorded at a sample rate of 250 Hz using the electrode positions: Fz, Cz, Pz, Oz, P3, P4, PO7 and PO8, according to the 10/20 international system. All channels were referenced to TP8 and grounded to position AFz. Signals were amplified by an acti-CHamp amplifier (Brain Products GmbH, Munich, Germany). The amplifier settings were 0.5 and 1000 Hz for the band-pass filter, the notch filter (50 Hz) was on, and the sensitivity was 500 µV. All aspects of EEG data collection and processing were controlled by the BCI2000 system (Schalk, McFarland, Hinterberger, Birbaumer & Wolpaw, 2004). A stepwise linear discriminant analysis (SWLDA) of the data was performed to obtain the weights for the P300 classifier and calculate the accuracy. The software used to design the interface was developed by the UMA-BCI group from the University of Malaga. This software is named UMA-BCI Speller and serves as the front-end to BCI2000. Neither online nor offline artifact detection techniques were employed.

2.3 The spelling paradigms

The present study used four different spellers that were handled and evaluated by the participants. All of them were initially based on the previously mentioned row-column lighted paradigm of Farwell & Donchin (1988). The only difference between the paradigms was the flashing stimuli employed for each condition (Figure 1). Our proposals used a graphical user interface with a 3 × 4 matrix and a writing space at the top, whose visual angle was equal to 23.54º × 16.31º (25 cm × 17.2 cm, 60 cm away) displayed on a 15.6-in (39.6 cm) screen at a refresh rate of 60 Hz. The interface presented 12 characters that could be selected: 10 letters, an underline as a space command and a delete button to correct the mistakes (denoted as “<”). The number of characters was adapted to 12 because the pictures had to be of an adequate size in order to be recognisable. In addition, a stimuli onset asynchrony (SOA) of 288 ms was used with an ISI of 96 ms, so that each stimulus was presented for 192 ms. The pause time between letters (i.e., between completed sequences of flashes) was equal to 5.47 s. The four presented paradigms were called: i) the excitatory pleasant picture paradigm (EPPP, high arousal and valence pictures), ii) the excitatory unpleasant picture paradigm (EUPP, high arousal and low valence pictures), iii) the neutral picture paradigm (NPP, low arousal and medium valence pictures) and, iv) the flashing letters paradigm (FLP). The purpose of the last two conditions was to serve as control conditions. On the one hand, the FLP had the purpose of serving as a control condition to study the effect of pictures as flashing stimuli. On the other hand, NPP served as a control condition to test whether differences between the paradigms with emotional pictures (i.e., EPPP and EUPP) versus the FLP were caused by the emotional charge.

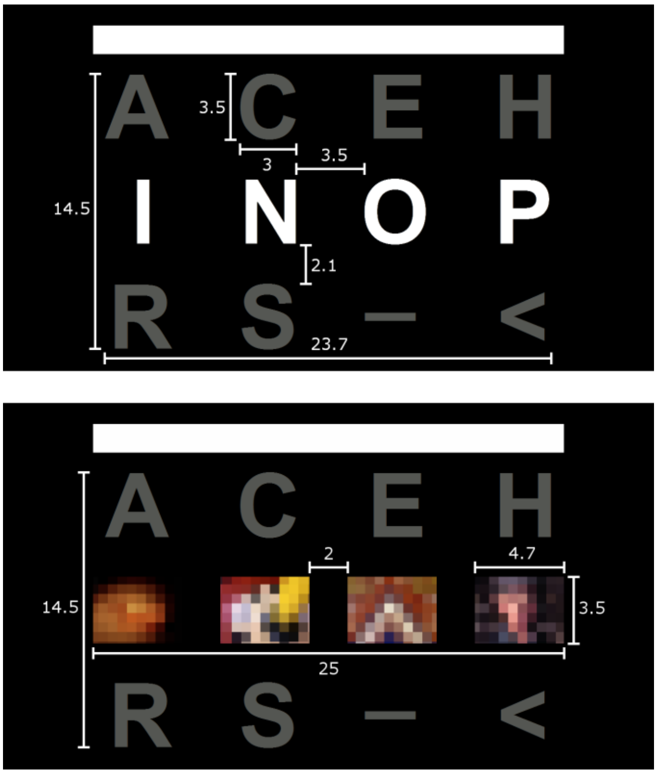

Figure 1. Size metrics (cm) for both types of interfaces employed: flashing letters and pictures. Due to copyright reasons, the condition with pictures has been pixelated.

All pictures of emotional conditions (i.e., EPPP and EUPP) were obtained from the IAPS (Table 1). On the one hand, the pictures of these conditions were selected using the following procedure: i) those pictures with high values of arousal (above the 90th percentile) and, then, ii) the 12 pictures with highest valence, for the EPPP, and the 12 with lowest valence, for the EUPP, were finally selected. On the other hand, for the NPP condition, the selected pictures were: i) those placed below the 10th percentile in arousal level and, then, ii) the first 12 pictures whose valence were nearer to the mean. The size of the pictures was 4.7 × 3.5 cm, presented at a distance of 60 cm (4.49º × 3.34º of visual angle). Moreover, only those pictures that maintained the proportion of the aforementioned size were selected, i.e., the pictures that filled all the space and did not have black padding. Those pictures with a predominance of dark colours or those that were excessively difficult to be recognised were also removed. In the FLP, the letters were adapted to be the same size as the figures, so they occupied the largest possible space within the aforementioned dimensions. The font used for the letters was arial bold, in upper case.

Table 1. The selected pictures of the International Affective Picture System (IAPS) presented in row-major order according to the user gender and speller condition.

Speller condition	Selected pictures	
	Gender	
	Man	Woman
Neutral picture paradigm (NPP)	7490, 7059, 2411, 5390, 7179, 5731, 7001, 7003, 7017, 7020, 8465, 7160	7020, 5471, 7050, 7055, 7010, 7161, 7179, 2190, 2397, 2840, 7041, 6150
Excitatory pleasant picture paradigm (EPPP)	4250, 4225, 8501, 4002, 4659, 4008, 4085, 4090, 4210, 4220, 8370, 8080	8001, 4525, 8030, 4668, 8370, 8179, 8180, 8186, 4698, 8490, 5621, 8158
Excitatory unpleasant picture paradigm (EUPP)	6563, 3131, 3000, 3130, 6510, 3060, 3068, 3069, 3071, 3080, 9250, 6231	3068, 3000, 3080, 3100, 3053, 3130, 9075, 3010, 9410, 9433, 3069, 3001

2.4 Procedure

The experiment was carried out in an isolated room where only the participant was present at the time he/she was performing the task, thus preventing external distractions. A within-subject design was used, so all users went through all experimental conditions. The study was performed in two different days and for two conditions per day. Due to experimental criteria, the time between sessions could not be less than four hours or longer than four days. The order of the speller's presentation was selected pseudo-randomly following a Latin square design, so that they were all equally distributed in order to prevent any unwanted effects, such as learning or fatigue effects.

All the conditions consisted of two parts: i) an initial calibration task to adapt the system to the user and ii) a writing task in which the user actually controlled the interface. Therefore, the main difference between both tasks was that in the first task the user did not receive any feedback.

Task 1. Calibration task. In this phase, the specific user parameters were not yet available for the corresponding speller, so he/she could not obtain any feedback of their performance. The user had to "write" six words of five letters, a total of 30 characters with a short break between words (variable at the request of the user). The number of sequences (i.e., the number of flashes per row and column) was prefixed to 10, so each stimulus was lit 20 times. The writing time for each character in this phase was equal to 20.06 s. Once these six words were "written", an offline analysis of the data was carried out to obtain the parameters that allowed him/her to continue with the session (task 2). The specific Spanish words were: "pares" (pairs), "chino" (Chinese), "presa" (dam), "hinco" (I sink), "raspe" (scratch) y "nicho" (niche).

Task 2. Online task. This test consisted of writing the phrase "CENO_EN_CASA" (I have dinner at home, in Spanish), a sentence of 12 characters (10 letters and 2 underlines) using the different speller matrices. In this task, the number of sequences was adapted according to the performance obtained in the calibration task (task 1). The number of sequences selected was that in which the user obtained his/her best accuracy for the first time from the second sequence. Thus, the number of sequences used ranged between 2 and 10. Due to the existence of feedback in this task, the user could make mistakes while spelling, so he/she had a command to delete the mistake and make a new attempt. The task ended once the user wrote the complete sentence.

At the end of each condition, the user had to complete a questionnaire in relation to his/her experience during the control of the paradigm.

2.5 Evaluation

For the calibration phase (task 1), different parameters were used to evaluate the effect of the stimuli type on the performance: i) the *accuracy* of the system classifying the letters (i.e., the number of correctly predicted letters divided by the total number of predicted letters), ii) the *information transfer rate* (*ITR*) (Wolpaw, Ramoser, McFarland & Pfurtscheller, 1998), and iii) specific ERP components. It should be advised that the pause between letters is not considered when calculating the *ITR*. The ERP components measured were divided into early potentials - P1 (80-130 ms), N1 (100-170 ms), P2 (180-230 ms) and N2 (220-300 ms) and late potentials - P300 (300-500 ms) and LPP (500-800 ms), based on the interval times used by Garrison et al. (2017). Each ERP component was measured according to the anterior (Fz and Cz) and posterior (Pz, Oz, P3, P4, PO7 and PO8) brain regions. The dependent variable was the *amplitude difference* between target and no target stimuli signals. This measure is important and is used in previous papers (e.g., Li et al., (2015) and Ma & Qiu, (2017)). This is because in a P300 BCI speller the target flashing stimuli has to compete with the no target flashing stimuli, which are both in the same category (e.g., in the EUPP, all flashing stimuli – target and no target – are excitatory and unpleasant pictures). Thus, due to the aim of improving the discrimination between a target and no target stimulus, measuring *amplitude difference* is, in our opinion, more convenient than directly measuring the target stimuli amplitude.

For the online task (task 2), the *accuracy*, the *ITR*, the *time* employed to complete the task, and the *correct commands per minute* (*CCPM*, i.e., the number of correctly selected commands divided by the total time invested) were used to obtain a more detailed view about the used metrics in a speller matrix assessment (Speier, Arnold & Pouratian, 2016). The time taken to type a letter was related to the used number of sequences (1.92 s to complete one sequence), so the *ITR* is affected by the selected number of sequences in the online task. Also, an *ad hoc* questionnaire was applied, to investigate the user's experience during the control of the device. This questionnaire required the rating of the following variables, ranging from 0 (very low) to 10 (very high): subjective perception of their performance (*performance*), difficulty to maintain attention on the interface (*attention*), required mental effort (*mental effort*), level of pleasure (*pleasure*), level of frustration (*frustration*) and level of general satisfaction felt using the interface (*satisfaction*).

The present study compared four different types of spellers. Therefore, for multiple comparison analysis, a correction method was applied so that, as the number of conditions increased, the chance of getting a type I error (i.e., reject null hypothesis when it is true) is raised. The Bonferroni correction method was used in the present study, so the used *p* value equal to 0.05 would be equivalent to 0.008 using the standard least significant difference method. In this way, despite losing some significant results that could be interesting, it can be affirmed that our conclusions will be based on robust effects, and not random.

It should be noted that participants E7 and E19 could not handle the FLP condition in the online writing task due to the fact that BCI2000 was unable to generate usable weights. Also, during the second session of user E22 (FLP and EUPP conditions), BCI2000 was unable to obtain usable weights due to instrumentation problems. Finally, the electrode Fz of the user E14 controlling the FLP and EUPP was not used in the ERP waveform analysis section due to the artifact interference observed in the exploratory analysis. These data were not included in the analysis of the performance or ERP waveform.

3. Results

3.1 Calibration task

3.1.1 Performance metrics. First of all, two repeated two-way measures ANOVA (4 × 10) including the speller (FLP, NPP, EPPP and EUPP) and sequence (10 sequences) factors were carried out. The difference between both ANOVA was the dependent variable used: the accuracy and the ITR (Figure 2 and 3, respectively). For both variables, the analysis showed the main effect of the speller (accuracy, F (3, 57) = 30.343, p < 0.001; ITR, F (3, 57) = 43.106, p < 0.001) and sequence (accuracy, F (9, 171) = 46.482, p < 0.001; ITR, F (9, 171) = 292.334, p < 0.001). Regarding interaction effects, significant results were shown by speller × sequence for accuracy (F (27, 513) = 10.995; p < 0.001) and ITR (F (27, 513) = 40.962, p < 0.001).

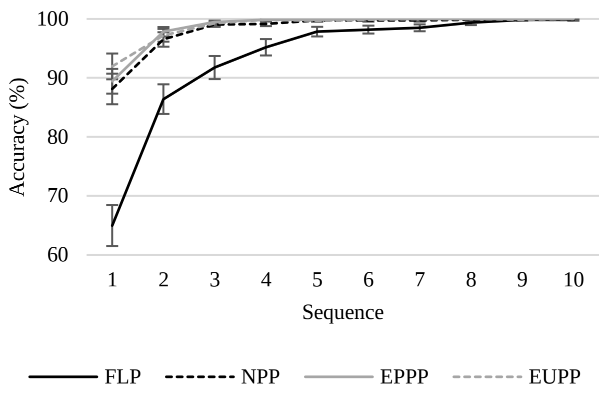

Figure 2. Accuracy (mean ± standard error) of the different P300-speller conditions as a function of the number of sequences.

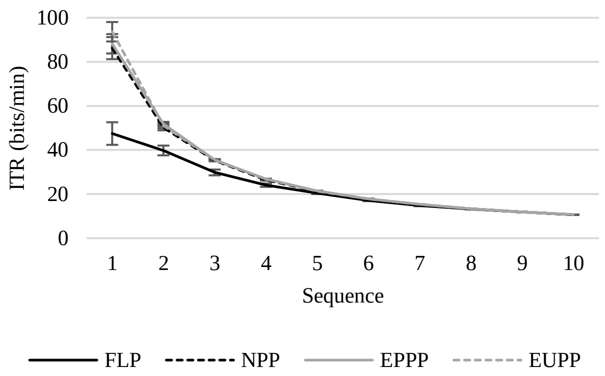

Figure 3. Information transfer rate (mean ± standard error) of the different P300-speller conditions as a function of the number of sequences.

Multiple comparisons of the *speller* factor showed the following significant results: FLP (93.19 ± 10.81 %; 22.92 ± 12.52 bits/min) versus NPP (98.17 ± 3.67 %; 28.84 ± 23.62 bits/min) (*p* < 0.001, for *accuracy* and *ITR*), EPPP (98.65 ± 3.31 %; 29.32 ± 24.29 bits/min) (*p* < 0.001, for *accuracy* and *ITR*) and EUPP (98.78 ± 2.54 %; 29.77 ± 25.71 bits/min) (*p* < 0.001, for *accuracy* and *ITR*). Thus, all picture conditions offered a significantly higher *accuracy* and *ITR* than the FLP, but there were no significant differences between picture conditions. Regarding the interaction effect found in *speller* × *sequence* for *accuracy* and *ITR*, significant differences (*p* < 0.05) between FLP and picture conditions (NPP, EPPP and EUPP) were observed individually in the first four sequences, but not from the fifth. In addition, it should be remarked that seven participants achieved 100% *accuracy* from the first sequence using the NPP (P2, P3, P7, P8, P10, P13, P22) and eight participants using the EPPP (P2, P6, P7, P8, P10, P13, P19, P22) and EUPP (P2, P7, P8, P10, P12, P13, P22, P23).

3.1.2 ERP waveform. Figure 4 shows the grand average ERP waveform for target and non-target stimuli as a function of the four tested conditions.

A one-way, repeated measure ANOVA (4) was carried out with the *speller* factor independently for each ERP component

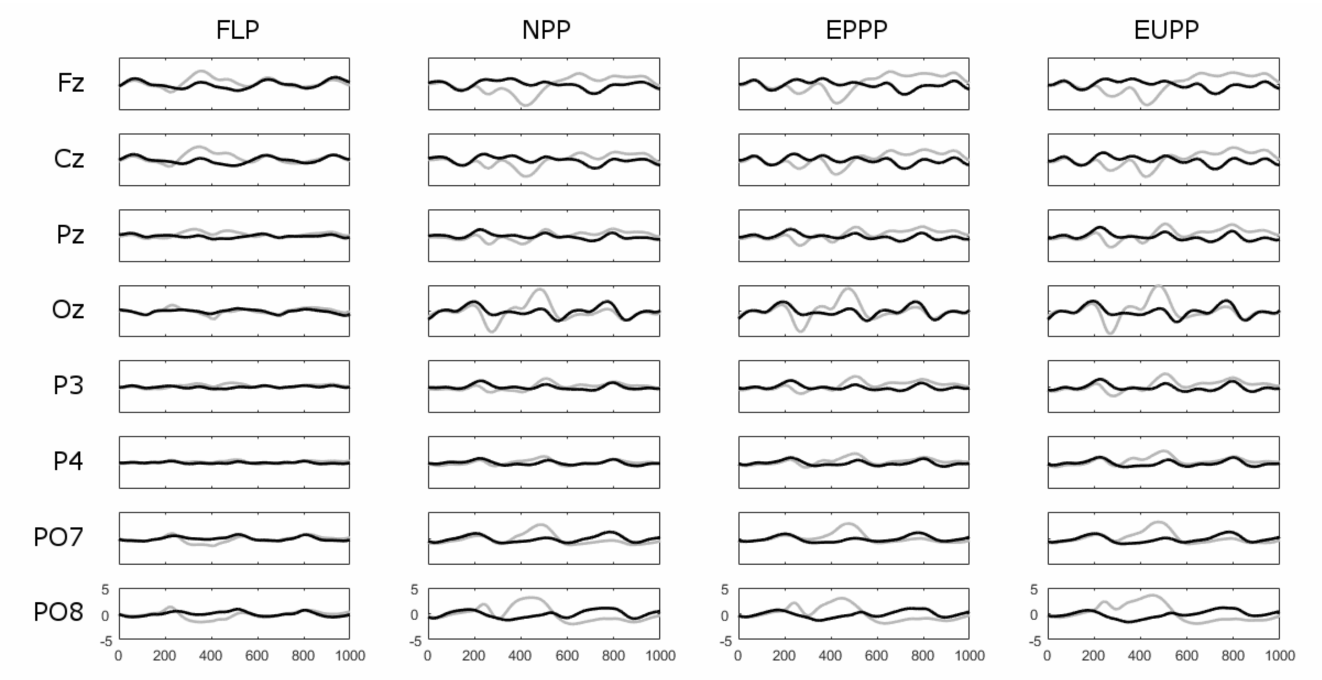

Figure 4. Grand averaged ERP waveforms for target (grey) and non-target stimuli (black) for the eight electrodes and spellers used (flashing letter paradigm (FLP), neutral pictures paradigm (NPP), excitatory pleasant picture paradigm (EPPP) and excitatory unpleasant picture paradigm (EUPP)).

(i.e., P1, N1, P2, N2, P300 and LPP) and each brain region (anterior and posterior). The dependent variable was the *amplitude difference* between target and no target stimuli signals. Table 2 shows the *amplitude difference* values between target and no target stimuli, as well as the significant differences that were obtained through the ANOVA for the anterior and posterior brain regions. Figures 5 and 6 have been added to illustrate the evolution of the *amplitude difference* for each speller.

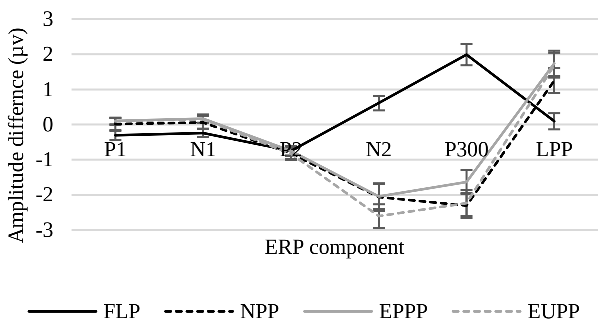

Figure 5. Amplitude differences (mean ± standard error) at anterior region (Fz and Cz channels) between target and no target stimuli signals for each event-related potential (ERP) component and speller (flashing lightning paradigm (FLP), neutral pictures paradigm (NPP), excitatory pleasant picture paradigm (EPPP) and excitatory unpleasant picture paradigm (EUPP)).

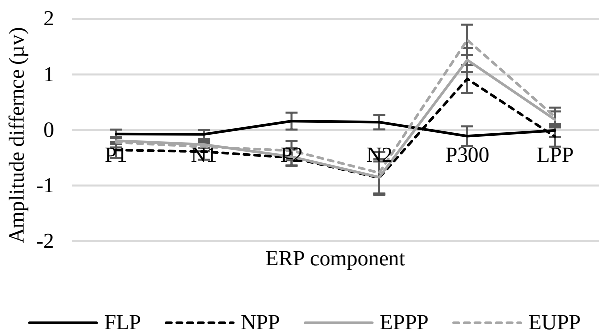

Figure 6. Amplitude differences (mean ± standard error) at posterior region (Pz, Oz, P3, P4, PO7 and PO8 channels) between target and no target stimuli for each event-related potential (ERP) component and speller (flashing lightning paradigm (FLP), neutral pictures paradigm (NPP), excitatory pleasant picture paradigm (EPPP) and excitatory unpleasant picture paradigm (EUPP)).

3.2 Online task

The average number of sequences used for each condition in the online task was: FLP, 5.1 ± 2.13; NPP, 2.91 ± 1.53; EPPP, 2.52 ± 0.9; and EUPP, 2.6 ± 1.05. Three one-way repeated measures ANOVA (4) with the *speller* factor were carried out, i.e., one ANOVA for each employed variable in the online task: *accuracy*, *ITR*, *time* (time to write the phrase) and *CCPM*. This factor offered significant differences for all of them: *accuracy* (F (3, 57) = 8.81; p = 0.002), *ITR* (F (3, 57) = 31.766; p < 0.001), *time* (F (3, 57) = 19.598; p < 0.001) and

TABLE 2. Average amplitude differences (μV, mean ± standard deviation) between target and no target stimuli for all participants (N = 23) of each event-related potential component in each brain region.

Signal	Place	Speller			
		(1) FLP	(2) NPP	(3) EPPP	(4) EUPP
P1	Anterior	-0.31 ± 0.63 [3, 4]	0.01 ± 0.83	0.1 ± 0.46 [1]	0.09 ± 0.47 [1]
	Posterior	-0.07 ± 0.37	-0.36 ± 0.68	-0.19 ± 0.28	-0.22 ± 0.45
N1	Anterior	-0.24 ± 0.59 [3, 4]	0.06 ± 0.93	0.17 ± 0.56 [1]	0.15 ± 0.48 [1]
	Posterior	-0.08 ± 0.38	-0.39 ± 0.69	-0.26 ± 0.29	-0.3 ± 0.4
P2	Anterior	-0.75 ± 0.69	-0.83 ± 0.89	-0.75 ± 0.63	-0.84 ± 0.67
	Posterior	0.16 ± 0.73 [2, 3]	-0.5 ± 0.72 [1]	-0.48 ± 0.75 [1]	-0.37 ± 0.84
N2	Anterior	0.61 ± 1 [2, 3, 4]	-2.07 ± 1.89 [1]	-2.05 ± 1.72 [1]	-2.61 ± 1.61 [1]
	Posterior	0.14 ± 0.62 [2]	-0.86 ± 1.41 [1]	-0.85 ± 1.55	-0.77 ± 1.78
P300	Anterior	1.99 ± 1.46 [2, 3, 4]	-2.31 ± 1.69 [1]	-1.64 ± 1.62 [1]	-2.24 ± 1.78 [1]
	Posterior	-0.11 ± 0.84 [2, 3, 4]	0.92 ± 1.2 [1, 4]	1.26 ± 1.05	1.62 ± 1.32 [1, 2]
LPP	Anterior	0.03 ± 0.73 [2, 3, 4]	1.2 ± 1.17 [1, 3, 4]	1.69 ± 1.14 [1, 2]	1.75 ± 1.17 [1, 2]
	Posterior	0.15 ± 0.46	-0.09 ± 0.72	0.19 ± 0.58	0.22 ± 0.66

Note: Anterior place corresponds to electrodes Fz and Cz, and posterior place corresponds to electrodes Pz, Oz, P3, P4, PO7 and PO8. Flashing letters paradigm (FLP), neutral pictures paradigm (NPP), excitatory pleasant picture paradigm (EPPP) and excitatory unpleasant picture paradigm (EUPP). Significant differences ($p < 0.05$) are denoted with a superindex to show which condition average was different to (1 for FLP, 2 for NPP, 3 for EPP and 4 for EUPP). The Bonferroni correction was applied.

TABLE 3. Accuracy, information transfer rate (ITR) time and correct commands per minute (CCPM) – mean ± standard deviation – in the online task for the different spellers and combinations.

Variables	Speller			
	(1) FLP	(2) NPP	(3) EPPP	(4) EUPP
Accuracy (%)	92.83 ± 8.22 [2, 3, 4]	99.17 ± 3.73 [1]	99.64 ± 1.6 [1]	98.93 ± 2.62 [1]
ITR (bits/min)	21.76 ± 12.1 [2, 3, 4]	42.6 ± 14.76 [1]	46.07 ± 11.93 [1]	44.37 ± 12.68 [1]
Time (s)	231.41 ± 90.04 [2, 3, 4]	134.96 ± 39.86 [1]	126.72 ± 24.65 [1]	131.53 ± 32.37 [1]
CCPM	3.81 ± 1.17 [2, 3, 4]	5.69 ± 1.07 [1]	5.86 ± 0.85 [1]	5.75 ± 0.94 [1]

Note: Flashing letter paradigm (FLP), neutral picture paradigm (NPP), excitatory pleasant picture paradigm (EPPP), and excitatory unpleasant picture paradigm (EUPP). Significant differences between spellers ($p < 0.05$) are denoted with a superindex to show which speller average was different (1 for FLP, 2 for NPP, 3 for EPPP, and 4 for EUPP). The Bonferroni correction was applied.

CCPM (F (3, 57) = 30.877; $p < 0.001$). The multiple comparisons between conditions for each variable are shown in Table 3. According to these results, the picture conditions (NPP, EPPP and EUPP) obtained the best results for the four variables.

3.3 Subjective questionnaires

With reference to the results obtained by the questionnaire, the *speller* factor offered significant results for the following variables: *performance* (F (3, 54) = 13.46; $p < 0.001$), *attention* (F (3, 54) = 9.139; $p < 0.001$), *mental effort* (F (3, 54) = 8.093; $p < 0.001$), *comfort* (F (3, 54) = 6.399; $p = 0.003$), *frustration* (F (3, 54) = 12.314; $p < 0.001$), *pleasure* (F (3, 54) = 8.81; $p = 0.001$) and *satisfaction* (F (3, 54) = 6.278; $p = 0.004$). The average score for each factor and the corresponding multiple comparisons between them are presented in Table 4. For most variables, the FLP speller related to the worst values, offering significant differences versus the other conditions; for *pleasure* and *satisfaction* variables, the FLP did not offer significant differences versus the EUPP.

4. Discussion

In general terms, the superiority of the paradigms with pictures has been shown in the study, from the calibration and online testing until the ad hoc questionnaires.

TABLE 4. Scores (mean ± standard deviation) for the variables collected in the subjective questionnaire for the different P300-speller conditions.

Variable	Speller			
	(1) FLP	(2) NPP	(3) EPPP	(4) EUPP
Performance	7.7 ± 1.56 [2, 3, 4]	9.55 ± 0.69 [1]	9.3 ± 1.03 [1]	9.3 ± 0.98 [1]
Attention	7.15 ± 2.11 [2, 3, 4]	8.8 ± 0.95 [1]	8.85 ± 1.35 [1]	8.75 ± 1.16 [1]
Mental effort	5.15 ± 3.2 [2, 3, 4]	3.4 ± 2.95 [1]	3.5 ± 2.69 [1]	3.7 ± 3.15 [1]
Pleasure	7.25 ± 2.17 [2, 3]	8.7 ± 1.13 [1, 4]	9.05 ± 1.39 [1, 4]	6.5 ± 3.3 [2, 3]
Frustration	4 ± 3.06 [2, 3, 4]	1.25 ± 1.62 [1]	1.35 ± 2.08 [1]	1.2 ± 1.96 [1]
Satisfaction	7.9 ± 2 [2, 3]	9.35 ± 0.99 [1]	9.35 ± 1.27 [1]	8.85 ± 1.53

Note: Flashing letter paradigm (FLP), neutral picture paradigm (NPP), excitatory pleasant picture paradigm (EPPP), and excitatory unpleasant picture paradigm (EUPP). Significant differences between spellers ($p < 0.05$) are denoted with a superindex to show which speller the average was different to (1 for FLP, 2 for NPP, 3 for EPPP, and 4 for EUPP). The Bonferroni correction was applied.

4.1 Calibration task

4.1.1 Performance metrics. Firstly, in the calibration task, the performance between the picture and letter conditions (measured through *accuracy* and *ITR*) offered significant differences until the fourth sequence. After this sequence, the superior performance of the picture interfaces could not be observed. While the FLP took four sequences to obtain a performance greater than 95% *accuracy*, the conditions with pictures needed only two sequences to achieve that score. 30 to 35% of the participants, depending on the condition, achieved 100% *accuracy* from the first sequence using some of the picture conditions.

The obtained accuracy cannot be fairly compared with that presented by other articles since our proposal had a clear advantage: our matrix had only 12 stimuli (i.e., 12 commands), while the most common number of stimuli are 36. However, the high *ITR* observed in the present work can be compared with other studies, since the *ITR* is adjusted to the number of commands present in the interface. The picture conditions (NPP, EPPP and EUPP) achieved an average *ITR* above 85 bits/min in the first sequence (NPP, 86.23 ± 23.97 bits/min; EPPP, 88.19 ± 21.03 bits/min; EUPP, 93.65 ± 20.67 bits/min). That score was higher than that obtained by the green familiar face paradigm, for example, presented by Li et al. (2015), i.e., ~55 bits/min. Also, between 7 and 8 participants (who reached 100% accuracy in the first sequence), depending on the condition, achieved an *ITR* equal to 111.97 bits/min in the first sequence of calibration using the picture conditions (NPP, EPPP and EUPP), something that was not achieved by any participant using the FLP.

4.1.2 ERP waveform. In the analysis of the ERP waveform, the emotional picture conditions (EPPP and EUPP) offered the largest amount of significant differences, especially versus the FLP. The early potentials (P1, N1, P2 and N2) were influenced by the use of pictures versus letters. At the anterior brain region, it is interesting to observe how only the emotional conditions (EPPP and EUPP) showed significant differences versus the FLP condition in the first two registered potentials (P1 and N1), i.e., from 80 to 170 ms following picture onset. These results may suggest an early image processing related to emotional stimuli versus the neutral ones at the anterior brain region. This would be in line with what was observed by Chen, Zhang & Jiang (2018) and Garrison et al. (2017), who showed significant differences between emotional and neutral pictures for target stimuli amplitude in early potentials. However, none of these papers reported an effect of emotion in P1 or N1. The greatest dissociation between the sets of pictures (NPP, EPPP and EUPP) and the FLP took place in the anterior region for the N2 potential, where both types of stimuli begin to clearly dissociate just after they have been found completely overlapped for P1 (Figure 5).

With reference to late potentials (P300 and LPP), the effect of pictures (NPP, EPPP and EUPP) versus FLP, is even greater than the one found in the early potentials (with the exception of N2, which is at the limit between early and late potentials). This effect has been observed in all late ERP components and brain regions, with the exception of LPP in the posterior region, where there were no significant differences at all. These results are in accordance with the literature, since the LPP is mainly located in the frontal, central and parietal regions, but not in the occipital region (Cuthbert et al., 2000; Schupp et al., 2000). Moreover, in the present study, a clear effect of the negative pictures (EUPP) was found, which provoked a larger amplitude versus the neutral ones (NPP) in the P300 potential in the posterior region. On the other hand, for the LPP, both sets of emotional pictures (EPPP and EUPP) showed a larger amplitude versus the neutral pictures (NPP) in the anterior zone.

As a result of this study, it can be hypothesised as to why the picture conditions (NPP, EPPP and EUPP) obtained a higher performance versus the letters one (FLP) when controlling the P300-based speller presented. In Figures 5 and 6, there are clear *amplitude differences* for the picture conditions in the anterior and posterior brain regions, while for the FLP condition this difference is only presented in the anterior brain region, but not in the posterior region.

Finally, an interesting result in the anterior region that deserves to be commented on is the positive *amplitude difference* values for the FLP condition (i.e., the target was greater than the non-target) while, for the picture conditions, a clear pattern was found in which the *amplitude difference* was negative (i.e., the amplitude of the non-target was greater than that of the target). This dissociation between picture conditions and FLP took place in the anterior region for potentials N2 and P300. So this is the first published work using the variable *amplitude difference* in a P300-based speller with these kinds of pictures; similar results are not found in the literature. Thus, we believe that this effect should be studied more deeply in future works.

4.2 Online task

The differences found in the ERP waveform analysis, regarding the effect of pictures, were transferred to the performance of the participants on the online writing task. However, despite the emotional charge of the stimuli affecting the EEG signal, this effect was not translated to the online task performance. Similar results to the performance obtained in the calibration task were found in the online task, in which the conditions with pictures obtained better results for all variables (*accuracy*, *ITR*, *time* and *CCPM*).

The picture conditions (NPP, EPPP and EUPP) offered adequate results that could be compared with the main current flashing stimuli derived from the familiar faces paradigm proposed by Kaufmann et al. (2011) (also see Li Li et al., 2015). The average *accuracy* was close to 100% for all conditions with pictures (NPP, 99.17 ± 3.73; EPPP, 99.64 ± 1.6; EUPP, 98.93 ± 2.62). These results can be considered suitable if we take into account that 61-70% of the participants (depending on the picture condition used) used only two sequences in the online task.

The presented *ITR* was approximately 44 bits/min for conditions with pictures (NPP, 42.6 ± 14.76; EPPP, 46.07 ± 11.93; EUPP, 44.37 ± 12.68). Despite these adequate results, it could be convenient to change the established criterion to select the number of sequences in the online task, which could not be less than two. However, our results can still be compared with those presented to date using a modality of the face paradigm (e.g., ~32 bits/min in Jin et al. (2012), 42.6 bits/min in Cheng, Jin & Wang (2017) and 39 bits/min in Li et al. (2015)). Likewise, it should also be noted that our study could be improved by adding other breakthroughs that can be combined with the presented paradigm. Some of these additions can be the use of the paradigm checkboard or random set presentation (Yeom, Fazli, Ller & Lee, 2014), the use of semi-transparent pictures (Cheng et al., 2017) or the application of predictive keyboards (Ryan et al., 2011).

Despite the fact that *CCPM* is not the best measure of our study, the superiority of the picture conditions (NPP, EPPP and EUPP) versus the standard paradigm (FLP) has been corroborated. Additionally, it is important to note three points: i) the excessive time between two sets of sequences (i.e., the writing of each letter) of 5.47 s may not have been necessary, especially using a matrix size of 3 × 4 elements; ii) as explained for the *ITR*, maybe the criteria for choosing the number of sequences used in the online task should select the first sequence in those cases where users achieved 100% accuracy in that sequence; and iii) the *CCPM* has been performed with an accuracy close to 100%. The *CCPM* should not be interpreted in isolation, since a system that selects the elements very quickly will have a high *CCPM* but does not have to have a high rate of effective commands (e.g., a system with a 10% accuracy that writes 1 command per second will have a *CCPM* equal to 6 but it would be impossible to use it to communicate).

4.3 Subjective questionnaire

The questionnaires showed significant differences between the spellers with pictures and those with letters for the following variables: *performance*, *attention*, *mental effort* and *frustration*. In addition, it is interesting to see how the interfaces that have been most pleasant to control have been the NPP and the EPPP, versus the FLP and the EUPP, which was expected. It should be convenient to highlight that the pleasure produced by the FLP and the EUPP was similar (7.25 ± 2.17 and 6.5 ± 3.3, respectively). Finally, the two interfaces that produced the greatest satisfaction for the participants were the NPP (9.35 ± 0.99) and the EPPP (9.35 ± 1.27), with significant differences compared to the FLP (7.9 ± 2). No interface showed significant differences in *satisfaction* versus the EUPP (8.85 ± 1.53). These results can be explained by the score given by participants in *pleasure*; this indicates that the participants have considered the pleasure and the classic measures of performance (*accuracy* and *CCPM*) to establish their general satisfaction with the interface.

4.4 Limitations and possible solutions

Some limitations have been identified in the present work. Despite the fact that most P300 BCI spellers use a 6 × 6 matrix, we used a 3 × 4 matrix, due to the needed for selecting an adequate picture size. Thus, it is difficult to compare our results with other studies. However, it should be considered that it is possible to implement a keyboard with 12 stimuli that allows a complete writing (e.g., Ron-Angevin et al., (2015)). On the other hand, it is possible that the effect of the emotional stimuli could not be found due to the habituation effect. That is, the stimuli lost its capacity to provoke an emotional response in the user after repeated exposure (Codispoti, Ferrari & Bradley, 2006; 2007). This could be solved using a greater variety of emotional stimuli. Additionally, the emotional processing of the pictures is given in high latencies reaching its maximum amplitude around 1 s (Cuthbert et al., 2000). Therefore, selecting a time interval to generate the classifier until 800 ms from stimulus onset may not be enough to register the main differences between emotional and neutral pictures. Finally, it should be noted that the use of the Bonferroni correction could lead to the possible presence of type II errors (i.e., accepting a null hypothesis when it is false). Thus, some significant differences could have been missed. On the contrary, it should be affirmed that the significant results obtained in the present study show strong effects which are unlikely to be the result of randomness.

5. Conclusion

One of the objectives of the present work was to study if the effect of pictures can improve performance. It can be affirmed that the paradigms with pictures (i.e., NPP, EPPP and EUPP) have shown a higher performance at all levels of the study versus the classical FLP. However, the second objective of the study was to evaluate whether the effect of emotional pictures could improve the performance in a BCI speller online writing task (as previously found in other studies outside the BCI field). This last aim was only shown in the ERP analysis, but not in performance.

The greater effect on performance of the picture paradigms (independently of the emotional charge) may be due to different factors, such as the physical properties of the stimulus (e.g., colour, shape or size of the stimulus) or cognitive processing carried out by the users. Therefore, this study opens the door to future research that deepens the use of pictures in new paradigms and even improves the performance. Furthermore, these types of stimuli, in addition to acting as simple flashing stimuli to catch the user's attention, can be used directly as control commands in an augmentative and alternative communication (AAC) system (e.g., selecting a picture of a television to indicate that the user wants to watch it). Previous work in BCI has used pictograms as direct stimuli (Käthner et al., 2017; Holz, Botrel, Kaufmann & Kübler, 2015). Therefore, future research should continue testing the hypothesis of complexity of the stimulus and compare pictograms versus more complex stimuli in a BCI.

Regarding the results of the emotional picture conditions (EPPP and EUPP), they only showed differences in the ERP waveform analysis. However, new alternatives could be proposed to strengthen the effect of the emotionality of the stimuli and, thus, obtain significant results in online performance. Some examples of this could range from extending the processing time of the EEG signal to generate the classifier (going beyond 800 ms) or continue working with the elements of the picture itself. This last proposal about the pictures could go in the direction of offering the user stimuli adapted to him/her, such as the beloved couple of a participant or even spiders for someone with arachnophobia (the second at least for research purposes).

Despite the limitations already declared, the present picture paradigms can be compared to the best current proposals, such as the green familiar faces paradigm. Therefore, we believe that picture paradigms are a new alternative that should continue being studied.

Acknowledgements

This work was partially supported by the Spanish Ministry of Economy and Competitiveness through the projects LICOM (DPI2015-67064-R) and by the European Regional Development Fund (ERDF). Moreover, the authors would like to thank all participants for their cooperation.

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