Biological Psychology 119 (2016): 190 – 199

DOI: https://doi.org/10.1016/j.biopsycho.2016.07.009

WORKING MEMORY OF EMOTIONAL STIMULI: ELECTROPHYSIOLOGICAL CHARACTERIZATION

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Abstract

Memorizing emotional stimuli in a preferential way seems to be one of the adaptive strategies brought on by evolution for supporting survival. However, there is a lack of electrophysiological evidence on this bias in working memory. The present study analyzed the influence of emotion on the updating component of working memory. Behavioral and electrophysiological indices were measured from a 3-back task using negative, neutral, and positive faces. Electrophysiological data evidenced an emotional influence on the working memory sensitive P3 component, which presented larger amplitudes for negative matching faces compared to neutral ones. This effect originated in the superior parietal cortex, previously reported to be involved in N-back tasks. Additionally, P3 results showed a correlation with reaction times, where higher amplitudes were associated with faster responses for negative matching faces. These findings indicate that electrophysiological measures seem to be very suitable indices of the emotional influence on working memory.

Keywords: Working memory, N-back, Emotion, Faces, ERP, P3.

1. Introduction

Memorizing events associated with biologically relevant consequences (both positive and negative) is an efficient strategy favored by evolution. Indeed, studies on long term memory have shown that emotional information is preferentially encoded, consolidated, and retrieved, compared to non-emotional information (e.g., Hamann, 2001; Kensinger, 2004, 2007). However, the effect of emotion on working memory, a complex mnemonic system devoted to the temporary maintenance of relevant information (e.g., Baddeley, 2003; D'Esposito, 2007), is less well established. Within the working memory system, the *executive component* (e.g., Baddeley, 1996; 2003) may be of special interest when dealing with biologically relevant events (which are, by definition, emotional), because it has the function of regulating which part of the incoming information will be actively maintained in short-term memory (Miyake et al., 2000). Here, *updating* processes play a crucial role, since they are necessary for keeping track of the information managed by the working memory system (e.g., Miyake et al., 2000; Morris & Jones, 1990). Accordingly, a task tapping into these updating processes might be especially suitable for studying the emotional influence on working memory.

Updating tasks typically involve the online addition and subtraction of information in working memory. The present study will focus on the N-back task, a widely used measure for evaluating updating processes (e.g., Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Hockey & Geffen, 2004; Martínez et al., 2011; see Redick & Lindsey, 2013 for a review). In the N-back task, a sequence of stimuli is presented, and the participant is instructed to indicate whether or not the current stimulus matches the one that appeared N steps earlier in the

sequence. Reaction times and error rates are the most employed behavioral indices for measuring performance and for analyzing the underlying working memory processes. The load factor N can be adjusted to manipulate task difficulty. Controlling task difficulty across participants is an appropriate strategy in studies exploring cognitive processing of emotion, since cognitive load has been proposed to modulate the influence of emotional contents on cognitive processes (e.g., Pessoa, McKenna, Gutierrez, & Ungerleider, 2002; Van Dillen, Heslenfeld, & Koole, 2009). In dual tasks, cognitive load affects behavioral performance and event-related potentials (ERPs) amplitude in the same way as emotion (e.g., MacNamara, Ferri, & Hajcak, 2011; Van Dillen & Derks, 2012). Thus, in the present study (which employs a single task where emotion is the target), it seems advisable to control for difficulty, in order to ensure that differences between experimental conditions will be only due to the modulatory effect of emotion. One strategy to accomplish this purpose in N-back tasks, and which is adopted here, involves selecting participants who show their best performance in a particular N-back level (e.g., 3-back), while discarding those participants reaching levels above or below this threshold during a time limited training session (see Methods' section for further details). To the best of our knowledge, this is the first study considering the effect of emotion on working memory in which cognitive load has been equalized for all participants.

Regarding the updating process, behavioral studies employing emotional N-back tasks are not very numerous and results are not consistent. Thus, there is some evidence for an effect of valence. Specifically, happy faces have been found to be preferentially updated (Levens & Gotlib, 2010, 2012), and sad or fearful faces to produce higher interference in task performance (Kensinger & Corkin, 2003;

Levens & Gotlib, 2010, 2012). Nevertheless, other data indicate a preference for fearful faces during updating (Luo et al., 2014). On the other hand, there is also evidence from a study employing sexual and crime scenes, indicating that stimulus arousal facilitates the updating process (Lindström & Bohlin, 2011).

Along with behavioral indices, ERPs have also been employed as indices of working memory, since they are especially suitable for studying rapid cognitive processes due to their millisecond resolution. Working memory neural mechanisms are mostly reflected in late positivities, concretely, in the P3 component. In this context, P3 amplitude reflects resource allocation, with larger amplitudes associated with higher cognitive involvement; latency indexes classification speed, which is proportional to the time required to detect and evaluate a target stimulus (e.g., Kok, 2001; Polich, 2007). Previous electrophysiological data indicate that experiencing an induced negative emotional state when performing a spatial letter updating task may decrease posterior P3 amplitude (Li, Li, & Luo, 2006), which points to a modulating effect of emotion on this component. However, to the best of our knowledge, up to now there are no ERP studies on the emotional influence on working memory employing emotion as the target stimulus to be updated, and directly addressing the following key points: First, the most sensitive ERP component for measuring the influence of emotion on working memory, as well as its topography, has not yet been determined; neither has the effect of emotion on amplitude and latency been analyzed. Second, it has not been clarified whether the modulating effect of emotion on working memory performance is preferentially driven by valence (negative *or* positive), or by arousal (both negative *and* positive).

Accordingly, the present study explored these issues, administering an emotional single 3-back task using negative, neutral and positive faces as stimuli, and measuring behavioral and electrophysiological indices. Participants were selected according to their previous best performance during an N-back training session, discarding those reaching levels lower or higher than the 3-back level. This strategy ensures that the level of cognitive load —a crucial factor modulating working memory, as explained above— is homogenized across participants. Based on previous results mentioned earlier, an advantage of emotional faces (negative, or both negative and positive, compared to neutral ones) during the updating process was expected, as evidenced by lower reaction times, smaller error rates, and enhanced ERP amplitudes in the memory-sensitive P3 component.

2. Methods

2.1. Participants

Sixty students from the Universidad Autónoma de Madrid participated in the first session of this study (during which only behavioral data were measured). From this initial sample of 60 only those 23 who performed at the level of difficulty required for the experimental task (3-back) were selected for the second and main study (which also included electrophysiological measures). These remaining 23 participants (14 women) performed a 3-back task with emotional face stimuli (see Figure 1, as well as the Procedure section, for details on participant selection). Ages ranged from 18 to 32 (mean=22.4, SD=3.6). All students participated voluntarily, after providing their informed consent according to the Declaration of Helsinki. They received course credit or a monetary compensation for their

participation (€5 for the first session and €15 for the second session). They reported normal or corrected to normal visual acuity. The experiment was approved by the Research Ethics Committee of the Universidad Autónoma de Madrid.

*** Figure 1 about here ***

2.2. Stimuli and Procedure

As mentioned above, the study was composed of two sessions, held in sequence and separated by one week. Details are described in Figure 1. During the first session, in order to classify their optimum N-back level, the initial 60 participants were exposed to an adaptive N-back task employing neutral faces. Thirty-two face stimuli[1] were taken from the FACES database (Ebner, Riediger, & Lindenberger, 2010). Participants were placed in front of a computer screen at a distance of 40 cm. Stimuli were presented using an application designed for the purpose of the study, based on Visual Basic. The task was presented in 12 blocks; each block was composed of 20+N images (being N = 1, 2, 3, etc., depending on the participant's current level of difficulty in the N-back task) of which 6 were matches. Matches were those stimuli that matched the one appearing N steps earlier in the sequence, and non-matches were those that did not. In order to

[1] FACES database codes of the faces employed during session 1:
Neutrality_011_45, Neutrality_013_22, Neutrality_021_80, Neutrality_026_54, Neutrality_029_48, Neutrality_038_46, Neutrality_040_24, Neutrality_043_54, Neutrality_057_22, Neutrality_063_27, Neutrality_070_45, Neutrality_073_55, Neutrality_087_39, Neutrality_093_47, Neutrality_097_54, Neutrality_098_20, Neutrality_105_21, Neutrality_117_45, Neutrality_122_53, Neutrality_123_20, Neutrality_125_21, Neutrality_127_28, Neutrality_132_20, Neutrality_139_45, Neutrality_142_55, Neutrality_147_22, Neutrality_149_51, Neutrality_150_20, Neutrality_155_45, Neutrality_159_54, Neutrality_160_28, Neutrality_170_31.

control for confounding variables not related to the task, the same pictures were presented as matches and non-matches. Visual angle of all stimuli was 38° (width) × 29° (height), and they were displayed on the screen for 500 ms, followed by a fixation mark, located at the center of the screen, for 2500 ms. Participants were instructed to press the space bar of the keyboard when the current stimulus matched the one that appeared N steps earlier in the sequence. Each individual started at the 1-back level and progressed to the corresponding next level when committing less than three commission or omission errors during the current block. However, if five (or more) errors were committed, he or she was leveled down to the previous level. . Before starting the session, they completed a practice block of 20 images. Participants who had achieved the 3-back level after 12 blocks were invited to the next session (electroencephalographic (EEG) recording), held one week later. As indicated, this two-stage procedure was designed to homogenize the level of difficulty across participants. The 3-back level was chosen because it had been the one reached by most of the participants in a previous behavioral study using a similar experimental design (Román et al., 2015). All other participants, whose final maximum levels were found to be higher or lower than the 3-back level, were excluded.

During the second session, participants (n=23, as indicated) performed a 3-back task using negative, neutral, and positive faces, while behavioral and EEG data were recorded. They were placed in an electrically shielded, sound-attenuated and video-monitored room, approximately 1 m from the screen. Images were presented on a back-projection screen through a RGB projector using Inquisit 3 task programming software (Millisecond Software, 2008). Stimuli were of six different types: Negative Match, Neutral Match, Positive Match, Negative Non-

match, Neutral Non-match, and Positive Non-match. As explained, Matches were those stimuli that matched the one appearing three steps earlier in the sequence, and Non-matches were those that did not.

*** Figure 2 about here ***

Examples of stimuli and stimulation sequence in this second session are shown in Figure 2. Happy expressions were employed as positive stimuli, since expressions of positive valence other than happiness are problematic with respect to recognition rate (Tracy & Robins, 2008). In order to make the experimental design symmetrical, a single expression was also used as negative stimulus; disgust faces were selected, since, along with sad faces, their effect on ERPs has been shown to be quicker and more widely distributed than other negative expressions, such as anger or fear (Esslen, Pascual-Marqui, Hell, Kochi, & Lehmann, 2004). Moreover, the disgust expression shows a better recognition rate (in terms of both reaction time and accuracy) than other negative expressions, such as fear or sadness (Tracy & Robins, 2008). These face stimuli[2] were also taken from the FACES database (Ebner et al., 2010). Pictures of the three emotional categories

[2] FACES database codes of the faces employed during session 2 (models were the same for the three categories):
Disgust_003_46, Disgust_005_27, Disgust_006_30, Disgust_013_69, Disgust_017_19, Disgust_028_23, Disgust_037_54, Disgust_040_71, Disgust_051_22, Disgust_053_72, Disgust_061_73, Disgust_065_26, Disgust_073_53, Disgust_079_75, Disgust_082_22, Disgust_083_21, Disgust_084_78, Disgust_097_21, Disgust_112_73, Disgust_116_74, Disgust_126_27, Disgust_141_74, Disgust_156_72, Disgust_163_27.
Neutrality_003_46, Neutrality_005_27, Neutrality_006_30, Neutrality_013_69, Neutrality_017_19, Neutrality_028_23, Neutrality_037_54, Neutrality_040_71, Neutrality_051_22, Neutrality_053_72, Neutrality_061_73, Neutrality_065_26, Neutrality_073_53, Neutrality_079_75, Neutrality_082_22, Neutrality_083_21, Neutrality_084_78, Neutrality_097_21, Neutrality_112_73, Neutrality_116_74, Neutrality_126_27, Neutrality_141_74, Neutrality_156_72, Neutrality_163_27.
Happy_003_46, Happy_005_27, Happy_006_30, Happy_013_69, Happy_017_19, Happy_028_23, Happy_037_54, Happy_040_71, Happy_051_22, Happy_053_72, Happy_061_73, Happy_065_26, Happy_073_53, Happy_079_75, Happy_082_22, Happy_083_21, Happy_084_78, Happy_097_21, Happy_112_73, Happy_116_74, Happy_126_27, Happy_141_74, Happy_156_72, Happy_163_27.

were equivalent in luminosity [$F(2,46) = 0.5$, $p = 0.602$, $\eta^2_p = 0.022$], and contrast [$F(2,46) = 0.3$, $p = 0.664$, $\eta^2_p = 0.012$], as revealed by analysis of variance (ANOVA) applied on these variables with respect to Emotion (Negative, Neutral, Positive). Neutral faces employed during this session were different from those used in the training session. In order to discard effects of third variables, the same pictures were presented as matches and non-matches. Importantly, at the end of the recording session, participants filled out a bi-dimensional scale for each image, providing assessments on valence (ranging from negative/ unpleasant to positive/ pleasant) and arousal (ranging from calming to arousing), two theoretically orthogonal affective dimensions frequently used to explain the principal variance of emotional meaning (Lang, Greenwald, Bradley, & Hamm, 1993; Osgood, Suci, & Tannenbaum, 1957; Smith & Ellsworth, 1985). These subjective ratings are included in Table 1. Statistical analyses were carried out on these data to confirm, first, that stimulus valence was as assumed a priori and, second, that negative and positive faces were balanced with respect to their arousal levels. Repeated-measures ANOVAs were computed for both valence and arousal dimensions with respect to Emotion (Negative, Neutral, Positive). Results showed significant differences between Emotion categories for the dimension of valence [$F(2,44) = 369.7$, $p < 0.001$, $\eta^2_p = 0.94$], as well as for the dimension of arousal [$F(2,44) = 36.6$, $p < 0.001$, $\eta^2_p = 0.62$]. As expected, Bonferroni corrected post-hoc contrasts indicated that Negative and Positive faces showed different Valence [both $p < 0.001$] but not different Arousal levels [$p > 0.05$], and that they differed from Neutral ones in both Valence and Arousal [all $p < 0.001$].

Visual angle of all stimuli was 38° (width) × 29° (height), and they were displayed on the screen for 500 ms, followed by a white fixation cross on a black

screen for 2500 ms, so that the resulting stimulus onset asynchrony was 3000 ms. Participants were asked to look at the fixation cross, located at the center of the screen, and to refrain from blinking during stimulus presentation, to minimize ocular interference. They were also instructed to press —as accurately and rapidly as possible— one key if the current stimulus was identical to the stimulus that had appeared 3 trials before (Match stimulus), and another key if it was different (Non-match stimulus). There was a total number of 426 stimuli, which consisted of 36 Negative, 36 Neutral, and 36 Positive Match stimuli, as well as 108 Negative, 108 Neutral, and 108 Positive Non-matches. Trials were displayed in six different blocks (separated by rest periods) in semi-random order. Stimuli of each condition were equally distributed between blocks (6 Negative, 6 Neutral, and 6 Positive Match stimuli, as well as 18 Negative, 18 Neutral, and 18 Positive Non-matches within each block). Participants were asked to press the Match key with their right hand for half of the blocks and with their left hand for the other half. Furthermore, before starting the experiment, they completed a short practice block.

2.3. Recording and pre-processing

EEG activity was recorded using an electrode cap (ElectroCap International) with tin electrodes. Fifty-nine electrodes were placed on the scalp following a homogeneous distribution. Participants were seated inside an electrically shielded room that significantly avoided external interferences, and electrode impedances were kept up to 10 kΩ, in order to avoid excessive discomfort in participants, due to ethical reasons. All scalp electrodes were referenced to the nose-tip. Electrooculographic (EOG) data were recorded supraorbitally and infraorbitally

(vertical EOG), as well as from the left versus right orbital rim (horizontal EOG). An online analog bandpass filter of 0.3 Hz to 10 kHz was applied. Recordings were continuously digitized at a sampling rate of 420 Hz. The continuous recording was divided into 1000 ms epochs for each trial, beginning 200 ms before stimulus onset. Behavioral activity was recorded through a two-button keypad. An offline digital bandpass filter of 0.3 to 30 Hz was applied using Fieldtrip software (http://fieldtrip.fcdonders.nl; Oostenveld, Fries, Maris, & Schoffelen, 2011).

Outlier trials (responses before 250 ms or after 2000 ms) and trials to which participants responded erroneously, or to which they did not respond, were eliminated. Outlier limits were determined based on a previous behavioral study using a large sample (n=103) and a similar experimental design (Román et al., 2015), where 98 % of responses were given between 250 and 2000 ms. Ocular artifact removal was conducted through an Independent Component Analysis based strategy (Jung et al., 2000), as implemented in Fieldtrip. After this process, a second stage of visual inspection of EEG data was conducted. If any further artifact was present, the corresponding trial was discarded. The average number of trials accepted within each stimulus category after rejection of artifacts and incorrect responses is included in Table 1. A minimum criterion of 16 artifact-free and correct trials per condition and subject was set, in order to ensure an acceptable signal-to-noise ratio of the ERP averages.

2.4. Data analysis

In all statistical analyses employing ANOVA, post hoc comparisons were performed to determine the significance of pairwise contrasts using the Bonferroni correction

procedure. In order to break down interaction terms, simple effects analyses were conducted (i.e., comparisons of the effects of one independent variable between the levels of the other). Effect sizes were computed using the partial eta-square (η^2_p) method. The analyses were carried out using SPSS 19.0 software package (IBM SPSS, 2010).

2.4.1. Behavioral data

Given that behavioral data lacked normal distribution, data transformations were applied to the original values in order to achieve normality. Reaction times were logarithmically transformed ($\log_{10}$[reaction times]), as recommended for this kind of distribution (Tabachnick & Fidell, 2001), and error rates were arcsin-root transformed (arcsin[$\sqrt{}$error rates]), as appropriate for data which lie between an upper and lower bound (Zar, 1996). Statistical analyses were then performed on these normally transformed data, though Table 1 includes the original ones for facilitating interpretation. Reaction times and error rates were submitted to repeated-measures 2×3 ANOVAs, introducing Match (Match, Non-match) and Emotion (Negative, Neutral, Positive) as factors. Outliers were omitted in the analyses.

2.4.2. ERP data

2.4.2.1. Detection, spatio-temporal characterization, and quantification of relevant ERP components

In order to detect and quantify relevant ERP components, those components explaining most of the variance in the temporal and spatial domain were extracted through covariance-matrix-based principal components analysis (PCA). This technique has repeatedly been recommended for these purposes (e.g., Chapman & McCrary, 1995; Chapman, Hoag, & Giaschi, 2004; Dien, 2010, 2012; Dien, Beal, & Berg, 2005; Dien, Khoe, & Mangun, 2007). PCA determines components mathematically, avoiding subjectivity or inter-judge discrepancies, which often result from traditional window/ region definition based on manual or visual criteria. In the first step, temporal PCA (tPCA) computes the covariance between ERP time points, which tends to be high between those involved in the same component and low between those belonging to different components. The solution is a set of nearly independent factors made up of highly covarying time points, which directly correspond to ERP components. Extracted temporal factors are quantified in factor loadings and factor scores, which are linearly related to amplitudes, where amplitudes are a joint function of factor loadings and factor scores multiplied together (e.g., Dien, Tucker, Potts, & Hartry-Speiser, 1997; Dien et al., 2005, 2007). The decision on the number of factors to select was based on the scree test (Cliff, 1987). Extracted factors were submitted to promax rotation (Dien, 2010, 2012; Dien et al., 2005, 2007).

Once quantified in temporal terms, and prior to statistical contrasts on experimental effects, temporal factor scores were submitted to spatial PCA (sPCA), in order to decompose topographies at the scalp level into its main spatial regions. Thus, while tPCA separates ERP components with respect to time, sPCA separates them with respect to space, with each region or spatial factor ideally reflecting one of the concurrent neural processes underlying each temporal factor. This spatial

decomposition is an advisable strategy prior to statistical contrasts, since ERP components frequently behave differently in some scalp areas than in others (e.g., they present opposite polarity or react heterogeneously to experimental manipulations). Basically, each spatial factor is formed by the channels where recordings tend to covary. As such, the shape of the sPCA-configured regions is functionally based. Each spatial factor can also be quantified through spatial factor loadings and a spatial factor score, a single parameter that reflects the amplitude of the whole spatial factor. Similarly, the decision on the number of factors to select was based on the scree test, and extracted factors were submitted to promax rotation as well. Statistical analyses were computed on factor scores, which are linearly related to amplitudes, as explained above.

2.4.2.2. Scalp ERP analysis

Finally, repeated-measures 2×3 ANOVAs on spatial factor scores were carried out for the temporal factor corresponding to P3, with respect to Match (Match, Non-match) and Emotion (Negative, Neutral, Positive).

2.4.2.3. Source (3D) analyses

Global temporal factor scores (i.e., collapsed across subjects and conditions) were submitted to *exact low-resolution brain electromagnetic tomography* (eLORETA) in order to localize the source in which the component originated. eLORETA is a 3D discrete linear solution for the EEG inverse problem (Pascual-Marqui, 2002). Although solutions provided by EEG-based source-location algorithms should be interpreted with caution, due to their potential error margins, the use of tPCA-

derived factor scores instead of direct voltages (which leads to more accurate source-localization analyses: Carretié et al., 2004; Dien et al., 2010) contributes to reducing such error margins.

2.4.3. Behavior - ERP relationship

In addition to anterior analyses, in order to test the linkage between behavioral and ERP data, correlation analyses were carried out using Pearson's correlation coefficient.

3. Results

3.1. Behavioral data

Mean reaction times and error rates for each type of trial are presented in Table 1. Error rates differentiated significantly between Matches and Non-matches. Specifically, error rates were higher for Matches than for Non-matches [$F(1,22) = 65.6$, $p < 0.001$, $\eta^2_p = 0.749$]. This result is shown in Figure 3a. The main effect of Emotion and the interaction effect of Match × Emotion were non-significant [$F(1,44) = 1.3$, $p = 0.287$, $\eta^2_p = 0.055$; $F(2,44) = 0.4$, $p = 0.675$, $\eta^2_p = 0.018$, respectively]. ANOVAs performed on reaction times revealed a marginal interaction effect of Match × Emotion [$F(2,44) = 2.6$, $p = 0.087$, $\eta^2_p = 0.105$], however, Bonferroni corrected pairwise tests were non-significant [$p = 0.280$, $p = 0.354$, and $p = 0.999$, for Negative-Neutral, Positive-Neutral, and Negative-Positive, respectively]. Both main effects of Match and Emotion were non-significant

[$F(1,22) = 0.2$, $p = 0.662$, $\eta^2_p = 0.009$; $F(1,44) = 1.6$, $p = 0.222$, $\eta^2_p = 0.066$, respectively].

*** Figure 3 about here ***

3.2. ERP data

3.2.1. Detection, spatio-temporal characterization, and quantification of relevant ERP components

Figure 3 shows grand averages after subtracting the baseline activity (200 ms of pre-stimulus recording) from each ERP. These grand averages correspond to O1, where significant results are more visible. As explained above, in order to detect and quantify outstanding ERP components, tPCA was applied. As a consequence, six temporal factors (TFs) were extracted from the ERPs (Figure 4). sPCAs subsequently applied on temporal factor scores extracted two spatial factors (SFs) for each of the temporal factors: one anterior or fronto-central and another posterior or parieto-occipital.

*** Table 1 about here ***

3.2.2. Experimental effects on scalp ERP components

Factor peak latency and topography characteristics associated TF 2 (peaking at 414 ms) with the wave labeled P3 in grand averages. This label will be employed hereafter to make results easier to understand. Temporal factor loadings of P3 are

represented as line plot in Figure 4, and spatial factor loadings are shown as topographical plots. As previously indicated, amplitudes are a joint function of the factor loading waveform/ topographies and the factor scores multiplied together. The portion of the waveform/ topography accounted for by the factor with high loadings corresponds to P3 in the related domain.

Spatial factor scores of P3 were submitted to ANOVAs on Match (Match, Non-match) × Emotion (Negative, Neutral, Positive). Table 1 includes means and standard deviations of P3, and Figure 3 shows a summary of all relevant results. ANOVAs yielded a significant main effect of Match. The component presented greater amplitudes for Matches than for Non-matches in both anterior and posterior scalp regions [anterior P3: $F(1,22) = 81.8$, $p < 0.001$, $\eta^2_p = 0.788$; posterior P3: $F(1,22) = 102.4$, $p < 0.001$, $\eta^2_p = 0.823$]. Furthermore, there was a significant interaction effect between Match and Emotion in posterior regions [$F(2,44) = 3.7$, $p = 0.033$, $\eta^2_p = 0.143$], as illustrated in Figure 3b (topography shown in Figure 3c). Bonferroni corrected post hoc comparisons indicated that, within the Match condition, Negative faces elicited significantly greater ERP amplitudes than Neutral faces [$p = 0.042$], whereas amplitudes of Positive faces did not differ from those of Neutral or Negative ones [$p = 0.999$ and $p = 0.607$, respectively]. Further, comparing both Negative and Positive stimuli to Neutral ones within both levels of Match (Match, Non-match), the interaction effect was confirmed. The difference between Negative and Neutral faces varied significantly from Matches to Non-matches [$F(1,22) = 9.1$, $p = 0.006$, $\eta^2_p = 0.293$], while the difference between Positive and Neutral stimuli did not vary [$F(1,22) = 2.2$, $p = 0.151$, $\eta^2_p = 0.091$]. The main effect of Emotion was non-significant at both anterior and posterior scalp regions [$F(1,44) = 0.5$, $p = 0.607$, $\eta^2_p = 0.022$; $F(1,44) = 0.9$, $p =$

0.413, η^2_p = 0.039, respectively], as well as the interaction effect at anterior P3 [$F(2,44) = 1.2$, $p = 0.305$, $\eta^2_p = 0.053$].

Data were also analyzed via the traditional method, which determines temporal windows and scalp regions of interest through visual inspection of grand averages, in order to define components and quantify their direct amplitudes. The results of this method were similar to those obtained using PCA (see supplementary data).

3.2.3. Source (3D) analyses

As shown in Figure 3d, eLORETA analyses revealed the superior parietal cortex (Brodmann area 7) as the main focus of P3.

3.3. Behavioral - ERP relationship

Correlation analyses on behavioral data and P3 factor scores support the individual analyses reported above. Thus, a significant correlation between error rates and both anterior and posterior P3 factor scores was found [$r(136) = 0.362$, $p < 0.001$; $r(136) = 0.363$, $p < 0.001$, respectively], showing that higher error rates were associated with larger P3 amplitudes. Additionally, correlation analyses indicated that there was a significant relationship between reaction times and anterior P3 amplitude [$r(136) = -0.197$, $p = 0.021$]. In the case of posterior P3, there was a correlation with reaction times as well, but only for Negative Matches [$r(21) = -0.437$, $p = 0.037$], showing that faster reaction times were associated with larger posterior P3 amplitudes only when stimuli were Negative Matches. All

other correlations with posterior P3 were non-significant [$-0.223 \leq r(21) \leq 0.223$, $0.307 \leq p \leq 0.999$]. All correlation results are represented in Figure 5.

*** Figure 5 about here ***

4. Discussion

The main purpose of the present study was to provide electrophysiological evidence regarding the influence of emotion on working memory updating processes. Results are consistent with several previous behavioral findings indicating that emotional stimuli are indeed updated in a preferential way, as compared to neutral ones. This effect was reflected in posterior P3 amplitude, a characteristic working memory correlate. Moreover, the present study aimed to explore some properties of the emotional influence that are not well established in previous literature. Concretely, it attempted to clarify the role of emotional valence (negative *or* positive) or arousal (both negative *and* positive) in the affective modulation of working memory. To this end, an emotional 3-back task was administered, using negative, neutral, and positive faces as stimuli, while behavioral (reaction times and error rates) and neural (ERP) indices of working memory performance were recorded.

First, behavioral and electrophysiological data confirmed that match- and non-match stimuli triggered different responses, thus, the task was sensitive to the desired process. Specifically, behavioral data showed higher error rates for matching than for non-matching stimuli, indicating that discarding a stimulus (i.e., identifying it as non-matching) seems to be easier than recognizing it as matching.

At the neural level, the task effect was indexed by P3, which presented augmented amplitudes for matches compared to non-matches. Data on error rates and P3 amplitudes showed a positive correlation, which provides them with consistency. The neural result is in line with existing data, since P3 amplitude has previously been associated with the extent of cognitive involvement necessary for implementing an updating task (Chen, Mitra, & Schlaghecken, 2008; Watter, Geffen, & Geffen, 2001). It has also been related to processes of stimulus comparison and identification, such as those required during the N-back task (Chen et al., 2008; Kok, 2001; Missonnier et al., 2007; Polich, 2007; Watter et al., 2001), where P3 amplitudes to probe stimuli that match an item in a stimulus set were larger than amplitudes of those that do not match. This implies that identifying a match within the stimulus sequence is related to increased cognitive resources reflected in the P3 component, which is consistent with the present behavioral outcomes indicating that match responses were more difficult than non-match responses. Similar results have also been observed in previous studies employing the N-back task (e.g., Gray, Chabris, & Braver, 2003), where match and non-match stimuli differed in difficulty and, thus, triggered different processes. This may be due to the fact that discarding a match (i.e., detecting a non-match) is possible after perceiving a single different element, whereas identifying a match requires an exploration of the whole stimulus. Moreover, another important reason that contributes to the difference in P3 amplitude of matches and non-matches is the elevated repetition rate and probability of non-matches compared to matches: Given that there are three times more non-matches than matches, amplitude associated with non-matches is necessarily smaller (Polich, 2007; Watter et al., 2001).

Second, the influence of the emotional targets on the updating process was also reflected in the working memory sensitive P3 component, which, to the best of our knowledge, is a novel finding. As noted, the present study explored the differential influence of stimulus valence/ arousal, and the results evidence a valence effect on updating. Specifically, posterior P3 amplitudes were larger for negative faces than for neutral faces within the match condition, suggesting a higher resource allocation and a deeper updating process of negative compared to neutral faces. This result was supported by a correlation with behavioral data, concretely with reaction times, which were faster when anterior P3 amplitudes were larger. However, in the case of posterior P3, greater amplitudes were only associated with shorter reaction times in response to matching negative faces.

Consequently, only negative faces were better updated, while the processing of positive faces did not differ from neutral ones. This result suggests a valence but not an arousal effect, in favor of negative but not positive emotion, at higher order processing stages. These results are in line with previous behavioral data supporting a better updating of negative faces (Luo et al., 2014). They are also consistent with previous studies reporting this negativity bias towards facial expressions (e.g., Öhman, Lundqvist, & Esteves, 2001), evident in a particularly rapid detection and a more intense processing of negative faces compared to neutral or even positive ones. The negativity bias may be explained from an evolutionary perspective, where negative faces act as a primary communicative tool (e.g., Vuilleumier & Pourtois, 2007) and are most appropriate for activating defensive circuits. Numerous other ERP studies also support a preference towards negative faces at higher-order stages of stimulus processing (P3 and LPP: Chen, Sun, & Tong, 2012; Lang, Nelson, & Collins, 1990; Nakashima et al., 2008; Schupp et

al., 2004; Smith, Weinberg, Moran, & Hajcak, 2013; Tang, Li, Wang, & Zhu, 2009; Weinberg & Hajcak, 2010). In contrast, a positivity offset is observed at earlier, more automatic stages (P1 and N170: Batty & Taylor, 2003; Bayle & Taylor, 2010; Calvo & Beltrán, 2013; Chen et al., 2012; Leppänen & Hietanen, 2004; Liu et al., 2013; Nakashima et al., 2008). Furthermore, the present results are congruent with a larger framework of behavioral and electrophysiological evidence obtained from studies concerning selective attention, which have also described a consistent bias towards negative stimuli compared to neutral ones (for a review see Olofsson, Nordin, Sequeira, & Polich, 2008).

The origin of P3 was located, through eLORETA analyses, in the superior parietal cortex. Importantly, this area has been shown to be critical for the manipulation of information in working memory and has been previously related to performance in N-back tasks (Koenigs, Barbey, Postle, & Grafman, 2009; Owen, McMillan, Laird, & Bullmore, 2005; Sandrini, Fertonani, Cohen, & Miniussi, 2012).

Moreover, stimulus valence only influences match trials. This undermines a simple interference effect of emotion on the task, since such an effect would have been reflected in a significant emotional modulation of both matches and non-matches. An interference effect has been found in previous studies employing easier 2-back tasks, and most strongly when negative faces followed another incongruent facial expression (Kensinger & Corkin, 2003; Levens & Gotlib, 2010, 2012). Nevertheless, as stimulus valence only influences match trials, the valence effect cannot be segregated from the match effect. Results evidence that, within the match condition, negative faces were preferentially updated compared to neutral ones, as shown by higher P3 amplitudes. Thus, both negative valence and the

match condition surely contribute to this elevated call for processing resources, however, the extent of the contribution from each condition is unclear. This may be understood as a limitation of the present study inherent to the N-back task, which allows one to discard the interference effect but not to segregate the valence and match effects. Therefore, future studies should try to better discriminate valence effects and match effects by employing other tasks.

Furthermore, error data were more dispersed than expected, as shown by its standard deviation. Thus, the attempt to control difficulty a priori, in order to optimize the experimental design, was not completely successful, indicating a further limitation to the study. However, without controlling difficulty, standard deviation might have been even larger, given that some of the students discarded during the training session were not able to perform on the 3-back level. Thus, the procedure may indeed have helped to achieve a better design, however, it will be necessary to improve it for future studies (e.g., the duration of the training session may be increased or there may be more than one training session).

5. Conclusions

In conclusion, electrophysiological measures were suitable for uncovering the influence of emotion on working memory (as measured by a 3-back task), supporting the initial hypothesis of an advantage of emotional stimuli compared to neutral ones. This finding was evident in posterior P3 amplitude, as in previous working memory studies not dealing with emotion. Finally, the effect was related to the dimension of valence, rather than to arousal.

Acknowledgements

This work was supported by the grant PSI2014-54853-P from the Ministerio de Economía y Competitividad (Spain), and by the grant CEMU-2012-004 from the Universidad Autónoma de Madrid (Spain).

Appendix A. Supplementary data

Supplementary data can be found in the online version, at […].

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FIGURE LEGENDS

Figure 1. Schematic illustration of participant selection.

Figure 2. Schematic illustration of the emotional 3-back task. Note that these example pictures were not among the experimental stimuli.

Figure 3. Grand averages at O1 with global electrophysiological results and relevant behavioral results. (a) shows results for error rates (error bars indicate standard deviation): Matches > Non-matches for all emotional categories. (b) presents significant effects on posterior P3 amplitude: the main effect Matches (solid lines) > Non-matches (dotted lines); and the interaction effect Match × Emotion: Negative (red) > Neutral (black), only for Matches. (c) depicts the topography of posterior P3 at the scalp level, whereas (d) indicates the source of P3 at the 3D level.

Figure 4. PCA factor loadings after promax rotation: lines depict temporal loadings, and topographies represent spatial loadings. Temporal factor 2 (P3) is highlighted.

Figure 5. Scatter plots representing correlations between behavioral and ERP data. (a) Correlations of reaction times/ error rates with P3 at anterior/ posterior scalp regions: all correlation coefficients were significant, except for reaction times and posterior P3, where a significant association was found only for negative matches, as shown in (b).

Table 1. Means and standard deviations (in parenthesis) of: (i) subjective ratings of stimuli used during the 3-back task, (ii) average number of trials, (iii) behavioral data, and (iv) neural data (P3 factor scores, linearly related to amplitudes).

	Negative Match		Neutral Match		Positive Match		Negative Non-match		Neutral Non-match		Positive Non-match	
Subjective ratings of stimuli												
Valence (1=negative to 5=positive)	1.80	(0.27)	2.82	(0.17)	4.23	(0.38)	1.80	(0.27)	2.82	(0.17)	4.23	(0.38)
Arousal (1=calming to 5= arousing)	3.85	(0.36)	3.09	(0.21)	3.65	(0.40)	3.85	(0.36)	3.09	(0.21)	3.65	(0.40)
Trials												
Average number of trials accepted	19.8	(4.3)	19.6	(3.5)	19.4	(3.5)	63.0	(14.7)	65.5	(13.6)	63.5	(13.9)
Behavior												
Reaction times (ms)	825	(209)	792	203	827	197	827	192	817	190	810	174
Error rates (0-1)	0.32	(0.14)	0.30	(0.11)	0.32	(0.10)	0.12	(0.06)	0.10	(0.07)	0.11	(0.07)
Scalp level ERPs												
anterior P3 (factor scores)	0.54	(0.93)	0.33	(1.20)	0.41	(1.01)	-0.42	(0.75)	-0.34	(0.76)	-0.52	(0.75)
posterior P3 (factor scores)	0.67	(0.88)	0.27	(1.24)	0.43	(0.84)	-0.50	(0.81)	-0.36	(0.77)	-0.50	(0.74)