International Journal of Psychophysiology 155 (2020) 184–193

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Electrophysiological correlates of the differential outcomes effect in visual short-term memory

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A B S T R A C T

The differential outcomes procedure (DOP) consists in applying a specific outcome after each discriminative stimulus-correct response pairing, leading to improved performance in both memory and learning tasks (faster acquisition and/or higher response accuracy), compared to the non-differential outcomes procedure (NOP). The main aim of this study was to explore the electrophysiological correlates (ERPs) of the DOP in a visual short-term memory task, and to test whether a differential activation pattern would be observed depending on the outcomes condition (DOP vs. NOP). The ERP signals showed differences between both outcomes condition in all three phases of the short-term memory task: encoding, maintenance and retrieval. Our results are in accordance with the view that in the DOP condition the probe stimulus triggers a representation of the unique outcome, which remains active over the maintenance period (prospective process). In the NOP condition, in contrast, a representation of the probe stimulus is maintained (retrospective process). In addition, these results suggested that stimuli associated with unique outcomes captured attention involuntary at retrieval, decreasing the interference from distractor stimuli in the retrieval phase.

1. Introduction

The *Differential Outcomes Procedure* (DOP) consists in applying a specific outcome (e.g., picture of an object or animal) after each target stimulus or each distinct stimulus-correct response pairing. Typically, performance in both memory and learning tasks (better recognition, faster acquisition and/or higher response accuracy) is improved for DOP than for the non-differential outcome procedure (NOP), in which the outcome is not associated with a specific condition (NOP; for a review, see McCormack et al., 2019; Urcuioli, 2011). With regard to visual memory, this procedure has proved to be effective to improve: i) delayed recognition of objects in patients with Alzheimer's disease (Carmona et al., 2019b), in deaf children (López-Crespo et al., 2012) and in healthy children (Esteban et al., 2014b); ii) visuospatial working memory in mild cognitive impairment and in patients with Alzheimer's disease (Vivas et al., 2018), in children born prematurely (Martínez et al., 2012) and in healthy children (Esteban et al., 2015); iii) face recognition memory in children and in adults with Down's Syndrome (Esteban et al., 2014a), in older adults (López-Crespo et al., 2009) and in patients with Alzheimer's disease (Plaza et al., 2012).

Usually, delayed matching to sample tasks (DMST) have been used in the experimental studies exploring the possible benefits of the DOP in visual memory. The DMST involves three stages: i) encoding of the initial sample stimulus or cue (e.g., an oblate spheroid); ii) maintenance of stimulus information, during a brief delay of several seconds; and iii) retrieval of such information that enables the choice of the initial sample among the comparison stimuli. In addition, a feedback is displayed after each correct choice: a unique and specific outcome for each initial sample stimuli in the DOP condition (e.g., the correct selection of the oblate spheroid, the initial sample 1, always is associated with the photo of a white elephant, the outcome 1); or a random outcome in the non-differential outcomes procedure (NOP) condition (e.g., the oblate spheroid, the initial sample 1, can be followed sometimes by the photo of a white elephant, the outcome 1, and sometimes by the photo of a pink panther, the outcome 2).

Two theories explain the positive effect of the DOP: the expectancy theory (e.g., Overmier et al., 1971; Peterson and Trapold, 1980; Trapold, 1970; Trapold and Overmier, 1972) and the two-memory systems theory (Savage et al., 1999, 2004; Savage and Ramos, 2009). The latter theory is based on the former and is the most accepted and empirically-supported explanation of the DOP effects on learning and memory. The expectation theory (Overmier et al., 1971; Peterson and Trapold, 1980; Trapold, 1970; Trapold and Overmier, 1972) suggests that in discriminative learning tasks, an association is made between the initial stimulus and the outcome received after the correct response, so that when the initial stimulus is presented (e.g., the oblate spheroid),

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https://doi.org/10.1016/j.ijpsycho.2020.06.010
Received 17 November 2019; Received in revised form 10 June 2020; Accepted 22 June 2020
Available online 26 June 2020
0167-8760/

an expectation (a representation) of that outcome is activated (e.g., a white elephant). By administering differential outcomes, unique associations would be formed and, therefore, unique expectations associated with each distinct stimulus-correct response pairing would be activated. Furthermore, this theory assumes that behavior is guided by these expectations (goal-focused behavior), which would act as additional sources of information to the one provided by the discriminative stimulus. By contrast, in the NOP, expectations would not be unique or specific and so would not represent an additional source of information. They could not, therefore, influence the selection of the correct responses.

The two-memory systems theory (Savage, 2001; Savage et al., 1999, 2004; Savage and Ramos, 2009) builds upon expectation theory, but goes beyond it in that it explicitly states that there are two different memory systems (prospective vs. retrospective) which are activated depending on whether the outcomes given are either differential or non-differential. When the outcomes are not differential, participants can only complete the task correctly if they explicitly remember the sample stimulus. In this case, a retrospective memory system would be involved, associated with the hippocampus and dependent on the cholinergic system. If the outcomes are specific, participants can also use the implicit information that comes from the unique association established between the sample stimulus and the specific outcome associated with it. In this case, when the sample stimulus is displayed, the expectation (or representation) of the outcome would be activated, triggering a prospective memory system associated with the amygdala and dependent on the glutamatergic system.

Several studies support the existence of these two memory systems, by demonstrating that when differential outcomes are applied, populations with an affected cholinergic system, such as the elderly or patients diagnosed with Alzheimer's disease, are able to improve their performance in recognition memory tasks (e.g., Carmona et al., 2019b; López-Crespo et al., 2009; Plaza et al., 2012; Vivas et al., 2018). According to the two-memory systems theory, this is due to the fact that the DOP would activate the preserved glutamatergic system related to prospective memory in these patients. However, when non-differential outcomes are used, they showed the typically observed memory difficulties due to an impaired retrospective memory.

A more direct support of this theory is provided by two studies exploring the cognitive and neural mechanisms underlying the DOP. Recently, Carmona et al. (2019a) reported benefits in visual recognition memory under unconscious conditions (the sample stimuli or the outcomes were subliminal) when the outcomes were differentially administered. Their results are in agreement with the two-memory systems theory suggesting than an implicit prospective memory process is activated under the DOP condition. Moreover, using functional magnetic resonance imaging (fMRI), Mok et al. (2009) found in healthy adults, similar to previous studies in animals (e.g., Savage et al., 2004), greater activation in the hippocampus when non-differential outcomes were administered, reflecting the important role of this neural structure in retrospective memory. On the other hand, when differential visual or auditory outcomes were used there was an increased activation of the posterior parietal cortex angular gyrus, possibly indexing prospective processing of information (or prospective memory). Furthermore, depending on whether the outcome used was visual or auditory in nature, modality-specific brain areas related to the processing of information of that particular sensory channel were activated during the delay period.

To date, despite the aforementioned two studies, the time course of cognitive processes underlying the DOP is still scarcely known. In this study, we aimed to explore the electrophysiological correlates of the DOP in a visual short-term memory task using event-related potential recordings (ERPs). We asked whether a differential ERP pattern would be observed depending on the outcomes condition (DOP vs. NOP). To this end, participants performed a delayed matching to sample tasks (DMST) while ERPs were recorded from the scalp. ERP recordings allow the offline analysis of cognitive processes during task performance with a temporal resolution in the range of milliseconds. To the best of our knowledge, ERPs have never been applied to examine the differential outcomes effect in memory or learning processes.

With regard to the behavioral results, based on a recent study using a similar task (Carmona et al., 2019a), we expected to find a better performance in the DOP than in the NOP condition, specifically, a higher percentage of correct responses. With regard to the ERP data, in accordance with two-memory systems theory (and earlier expectation theory), we expect to observe differential ERP effects under the DOP (an implicit prospective process should be observed) compared to the NOP condition (a retrospective process should be registered). In fact, different outcome processing depending on the DOP vs- NOP condition should affect all the three phases involved in short-term memory process: encoding, maintenance and retrieval.

Concerning the *encoding phase*, recent research suggests that stimuli-reward association biases the encoding of visual information by enhancing the perceptual representation of the reward stimuli (Gong and Li, 2014; Infanti et al., 2015). Indeed, current studies (Glazer et al., 2018; Novak and Foti, 2015; Pornpattananangkul and Nusslock, 2015) suggest a modulation of multiple ERP components by reward, distinguishing different sub-stages in reward anticipation that are implicated in the performance of the task: initial sample stimulus or cue evaluation (in the encoding and in the retrieval phase), motor preparation of the response and feedback anticipation (in the retrieval phase). According to these studies, distinct ERPs components are triggered in the encoding phase or initial sample stimulus evaluation stage: N200 (i), a negative-going fronto-central wave peaking between 250 and 350 ms after the initial sample onset; and P300 (i), positive-going centro-parietal wave peaking activated approximately 350–600 ms following the initial sample onset.

Importantly, we also expected to find topographical differences between the waves in the two experimental conditions in the delay period (*maintenance phase*). In agreement with the two-memory systems theory, in the DOP condition the initial stimulus would activate the representation of its unique outcome during such period, involving a prospective memory process. According to this hypothesis, we expect non-intentional (automatic) activation of the unique outcome representation during the delay period. If so, ERP components related to outcome processing following the feedback display should be found during the delay period. That is, the feedback P300 and the Positive-Slow Wave (PSW) elicited in centro-parietal regions, which has been associated with outcome processing (Novak and Foti, 2015; Pornpattananangkul and Nusslock, 2015; Ruchkin et al., 1990, 1995) should be observed during the delay period when differential outcomes were anticipated. By contrast, given that in the NOP condition an internal representation of the initial stimulus should be maintained over the delay to correctly solve the task, only a Negative-Slow Wave (NSW), involved in visual working memory maintenance, should be observed in fronto-central regions (Kuo et al., 2012; Mecklinger and Pfeifer, 1996; Ruchkin et al., 1990, 1992).

Regarding to the *retrieval phase* (comparison stimuli screen), both two memory systems theory and expectancy theory (e.g. Overmier et al., 1971; Peterson and Trapold, 1980; Trapold and Overmier, 1972) suggests that in the DOP condition behavior is guided by the specific outcome expectation associated with each discriminative stimulus-correct response sequence (goal-focused behavior). This expectation might involve attentional mechanisms decreasing the interference from distractor stimuli due to the stimuli associated with outcomes capture endogenous attention involuntarily (Anderson et al., 2011a,b, 2014; Kuo et al., 2012; Zanto and Gazzaley, 2009). In such case, differences between experimental conditions in N100 components, reflecting attentional enhancement of visual processing, would be observed in parietal regions after the comparison stimuli onset (Downing, 2000; Olivers, 2007; Zanto and Gazzaley, 2009). Furthermore, once detected the sample stimulus among the comparison stimuli, both components associated with the cue evaluation, N200 (ii) in fronto-central (FC)

regions and P300 (iii) in centro-parietal (CP) regions (Glazer et al., 2018; Novak and Foti, 2015; Pornpattananangkul and Nusslock, 2015), would be elicited again in a different way under each outcomes condition (larger amplitude in the DOP than in the NOP). In addition, the contingent-negative variation (CNV) that reflects expectancies, and that is elicited during motor preparation of the response in our experimental context, taking the place of the readiness potential (Glazer et al., 2018), would be similarly registered after the comparison stimuli onset in both outcomes conditions. This negative wave is composed of an early frontal component (between 2000 and 1000 ms before the response), and a late central component (500 ms before the movement to response, approximately).

2. Method

2.1. Participants

Thirty undergraduates from the University of Almería (Spain), ranging in age from 18 to 35 years, participated in the experiment. Written informed consent was obtained from all participants. The study was approved by the University of Almería Human Research Ethics Committee, and it was conducted in accordance with the Declaration of Helsinki and its later amendments. Participants had normal or correct to normal vision and were naïve with respect to the purposes of the experiment. They received extra course credit for their participation in the study and the chance to win one of the prizes that were raffled off at the end of the study.

We conducted an a priori power analysis with the G*Power software 3.1.9.2 (Faul et al., 2007) to determine the minimum required sample size to detect main effects. The analysis showed that twenty-six participants were required to detect a large-medium effect size (d = 0.5), with alpha = 0.05 and power = 0.80. The effect size expected was based on previous studies concerning to the DOP in young healthy adults (e.g., Carmona et al., 2019a).

2.2. Setting and materials

The stimuli were displayed on a black background on a colour monitor (15-inch VGA monitor) of an IBM-compatible computer. The E-prime software (Psychology Software Tools Inc., 2012) controlled the stimulus presentation as well as the collection of the participant's responses (latency and accuracy data). Participants were tested individually in the same quiet room with identical sound and lighting conditions.

The stimuli were 6 white circular shapes with shaded sectors (see Fig. 1) designed with the Autocad software (Autodesk, 2010) by one of the authors (IC). Four of them were presented as initial sample stimuli and the remainder as comparison stimuli. The size of the shapes was 3° × 3° visual angle and they were displayed either individually at the center of the screen (sample stimulus), or in a 2 × 3 grid (comparison stimuli). Four reinforcers (a pen drive, a five-euro bill, a key ring or a set of four pens) were used in the experiment and they were raffled off at the end of the study. Pictures of these prizes were used as outcomes. They appeared at the center of the screen along with both a congratulation phrase ("very well", "well done", "congratulations" or "very good") and the phrase "you may win a" followed by the name of a reinforcer, after a correct choice. The phrases were in Courier New, size 12 and in white colour.

2.3. Procedure

Participants were randomly assigned to one of the two experimental outcomes conditions, differential (DOP; N = 15) and non-differential (NOP; N = 15). They were matched for age (DOP, M = 21.9, SD = 4.5; NOP, M = 21.4, SD = 4.2), sex (6 male and 9 female in each outcomes condition) and educational level. In the DOP condition, each to-be-remembered stimulus was associated with one specific outcome so that the correct response to a particular stimulus was always followed by its associated outcome. In the NOP condition, each correct response was followed by the random presentation of one of four possible outcomes (see Fig. 1).

All participants performed a DMST with a delay of 5 s between the offset of the stimulus sample and the onset of the comparison stimuli. Previous studies demonstrated a significant main effect of the outcome manipulation with this short delay (e.g., Carmona et al., 2019a; Esteban et al., 2015). The task, lasting approximately 20 min, comprised four practice trials followed by 96 experimental trials, grouped in two blocks of 48 trials each, so that each sample stimuli was displayed 12 times per block.

Stimuli sequence is depicted in Fig. 1. Each trial began with a fixation cross randomly presented for 500 or 1000 ms. After a blank screen of 500 ms, a visual sample stimulus was displayed for 1000 ms followed by a delay of 5000 ms with a blank screen. Then, six comparison stimuli (the sample stimulus plus five distractor shapes) appeared and remained on the screen until the participants responded by pointing with the computer's mouse to one of the shapes and by confirming the choice by pressing the left mouse button, or when 10 s were elapsed without a response. The position of the correct sample stimulus among the comparison stimuli was counterbalanced across trials. Following each correct response, the specific outcome was presented during 2000 ms. The screen remained blank after each incorrect response during the same time used for the outcome presentation. Trials were also scored as incorrect if the participant did not emit any response in 10 s.

2.4. Data recording and processing

The electroencephalogram (EEG) was continuously recorded from 30 scalp channels (actiCAP, Brain Products, Munich, Germany) mounted according to the international 10–10 system. A midfrontal electrode (FCz) served as reference channel. The ground electrode was located between Fpz and Fz. Additional electrodes were placed 1 cm below the right orbital ridge eye to record vertical electrooculogram (VEOG) and 1 cm lateral from the external canthi of left eye aimed at to record horizontal electrooculogram (HEOG).

In order to be able to re-reference the EEG data off-line to averaged mastoids, two electrodes were placed at left and right mastoid location. Impedance at all electrodes remained below 5 kΩ. An AC-coupled amplifier (BrainAmp, Brain Products, Munich, Germany) was used to digitize the electrical signals with a sampling frequency of 250 Hz (0.1–70 Hz band-pass, 50 Hz notch filter), digitally band-pass filtered (high cutoff: 25 Hz, 24 dB/octave attenuation; low cutoff: 0.1 Hz, 12 dB/octave attenuation). The BrainVision Analyzer 2.0 software (Brain Products, Munich, Germany) was used for the processing of EEG data.

The EEG data were corrected for ocular/blink artifacts using independent component analysis (ICA; Makeig et al., 1997). Later on, they were segmented from 200 ms pre initial stimulus onset to 2000 ms post comparison screen onset, and just trials with correct responses were included in the segmentation. EEG segments were corrected to a 200 ms baseline before the onset of the initial sample stimulus (i.e., the last 200 ms of the preceding black screen). EEG segments from retrieval phase (from 150 pre comparison stimuli onset to 2000 ms post comparison screen onset) were corrected to a 200 ms baseline before the onset of the comparison stimuli. Response times lower than 2000 ms were excluded from the analysis in order to avoid premature responses during the retrieval time window. Artifacts in each EEG segment and channel were reject automatically (maximal allowed amplitude ± 100 μV; maximal allowed voltage step 50 μV; maximal allowed difference of values in intervals 200 μV; lowest allowed activity 0.5 μV, interval length 100 ms). EEG signals in all channels were re-referenced off-line to averaged mastoids before the segments were averaged. The number

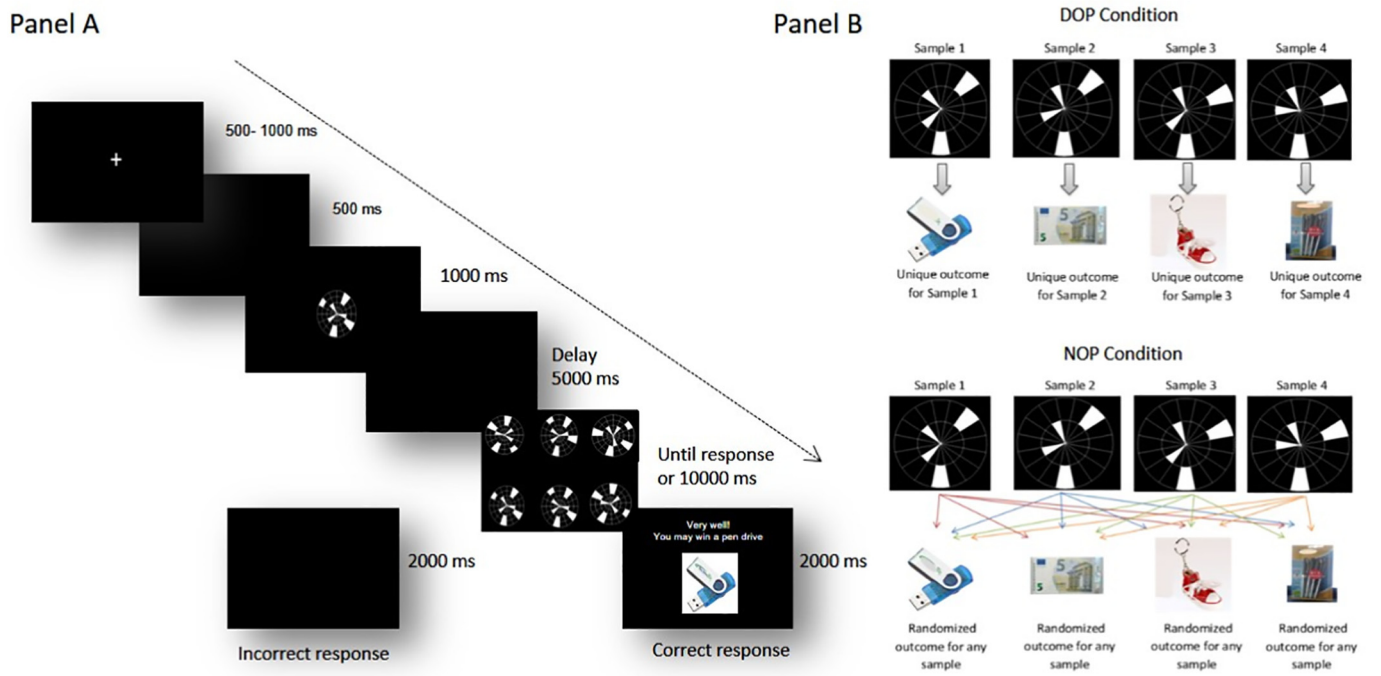

Fig. 1. Panel A. Stimuli sequence from left to right. Panel B. Stimuli-Outcomes association after correct responses in both conditions, differential outcomes procedure (DOP) and non differential outcomes procedure (NOP).

of averaged segments was greater than 45 (> 47% of valid trials) in all conditions, there were no significant differences in valid trials between outcome conditions.

Two regions of interest, fronto-central (FC) and centro-parietal (CP), were examined in order to explore N200, P300 and PSW components (Novak and Foti, 2015; Pornpattananangkul and Nusslock, 2015; Ruchkin et al., 1995), and N100, NSW and CNV (Kuo et al., 2012; Ruchkin et al., 1990; Zanto and Gazzaley, 2009). Six bilateral electrode pairs in the FC region and eight electrode pairs in the CP region were selected for statistical analyses: F3, FC1, FC5 (FC-left) and F4, FC2, FC6 (FC-right); C3, CP5, P3, P7 (CP-left) and C4, CP6, P4, P8 (CP-right).

2.5. Statistical analyses

Behavioral data (accuracy and correct response latency), were analyzed with a mixed analysis of variance (ANOVA) with outcome conditions (DOP vs. NOP) as the between-subject factor, and blocks (Block 1 and Block 2) as the within subjects factor (2 × 2).

Electrophysiological data were analyzed with mixed ANOVAs with outcome conditions as the between subject factor (DOP vs. NOP), and laterality (Left vs. Right) and caudality (FC vs. CP) as the within subjects factors (2 × 2 × 2), for all time windows, and ERP components of interest (average voltage data in each time windows). As we found in the behavioral data a significant main effect of outcome in each block and there was no significant interaction between variables block and outcome, block was not included as a factor in the electrophysiological analyses.

Kolmogorov-Smirnov test and Levene's test were conducted to check normality of data and homogeneity of variance, respectively. Results showed the normal distribution of data and the homogeneity of variance in all variables. Bonferroni correction has been applied to correct for type I error accumulation in multiple comparisons. Finally, we performed non-parametric tests, with a permutation approach (Monte Carlo method), in order to check the consistency and stability of the results obtained from the ANOVAs. The results have been included as Supplementary material.

2.5.1. Bayesian analyses

Bayesian factors were estimated in order to identify the probability of significant differences between ERPs signals in each time window under study and the baseline (zero value) in regions of interest, for both Outcomes conditions.

2.5.2. Correlation analyses

Pearson's correlation coefficient was used in all correlation analyses. These analyses were conducted to evaluate the relationship between behavioral measures of performance (correct responses and reaction times) and ERP activity in regions of interest, in each time window. Only significant correlations (*ps* < .05) are reported in the Results section.

3. Results

3.1. Behavioral results

3.1.1. Accuracy data

The analysis of correct responses (see Fig. 2) showed significant main effects of Outcomes condition [F (1,28) = 8.70, p = .006, η_p^2 = 0.24], indicating that participants were less accurate in the NOP (57% correct responses) than in the DOP condition (72% correct responses), and Block [F (1,28) = 7.17, p = .012, η_p^2 = 0.21], showing that performance was better in the second block (67%) than in the first block (62%). No significant interaction Outcomes condition x Block was found [F (1,28) = 0.24, p = .87, η_p^2 = 0.009].

3.1.2. Latency data

The analysis of latency data revealed a main effect of Block [F (1,28) = 4.34, p = .046, η_p^2 = 0.13], indicating that participant's correct responses were faster in the second block (3660 ms) than in the first block (3921 ms). No other effect nor interactions between the two factors were statistically significant (*ps* > .05).

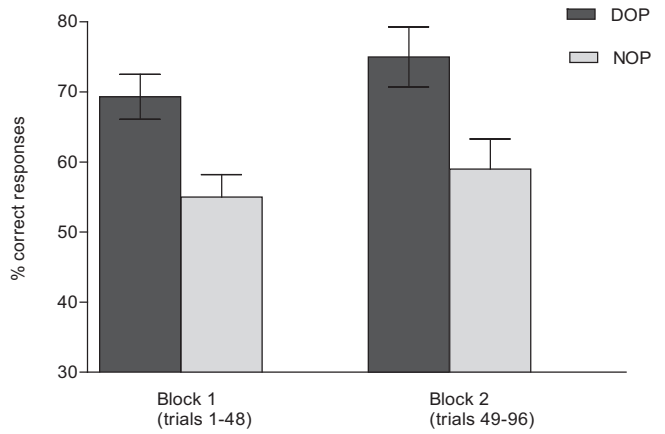

Fig. 2. Mean percentage of correct responses as a function of Outcomes (DOP, differential vs. NOP, non-differential) and Block (1 vs. 2). Error bars represent the standard deviations.

3.2. Electrophysiological data

3.2.1. Encoding phase

3.2.1.1. N200 (i). Time window from 250 to 350 ms after the initial stimulus onset. The ANOVA revealed a significant main effect of Caudality [F (1,28) = 4.5, p = .043, ηp^2 = 0.14] and Laterality [F (1,28) = 7.8, p = .009, ηp^2 = 0.13], that is, a greater activity in the CP region (mean = 2.6 μV, SD = ± 0.49) than in the FC regions (mean = 1.5 μV, SD = ± 0.49) was registered, as well as, the left hemisphere (mean = 2.4 μV, SD = ± 0.26) than in the right (mean = 1.69, SD = ± 0.26). The Outcome x Caudality interaction effect reached also significance [F (1,28) = 4.3, p = .048, ηp^2 = 0.22]. The analysis of that interaction revealed a significant main effect of Outcomes [F (1,28) = 17, p < .001, $\eta_p{}^2$ = 0.38] only in the FC region (see Table 1 for a summary of the results for the electrophysiological data). In the DOP condition a larger negativity (mean = .58 μV, SD = ± 0.32) than in the NOP condition (mean = 2.47 μV, SD = ± 0.32) was observed (see Fig. 3). No other significant effects nor interactions were found (ps > .05).

3.2.1.2. P300 (i). Time window from 350 to 550 ms after the initial stimulus onset. The mixed ANOVA showed a significant interaction effect Outcome x Caudality [F (1,28) = 4.9, p = .035, ηp2 = 0.15]. No significant main effects nor other interactions were found (ps > .05). Further analysis of the interaction revealed a main effect of Outcomes [F (1,28) = 9.10, p = .005, $\eta_p{}^2$ = 0.25] in the CP region. A higher positivity (mean = 3.6 μV, SD = ± 0.55) in the DOP condition than in the NOP condition (mean = 2.5 μV, SD = ± 0.55) was registered only in this region (see Fig. 3). No significant effects nor other interactions were found (ps > .05).

3.2.2. Maintenance phase

3.2.2.1. P300 (ii) and early PSW. Time window from 1350 to 1750 ms after initial stimulus onset (delay period; 350 to 750 ms after the initial stimulus offset). The ANOVA revealed a significant main effect of Outcomes [F (1,28) = 6.1, p = .02, $\eta_p{}^2$ = 0.47], such that the DOP condition showed greater activity (mean = 1.1 μV, SD = ± 0.38) than the NOP condition (mean = −.23 μV, SD = ± 0.38). No other main effect was found (ps > .05). The Outcomes x Caudality interaction was also significant [F (1,28) = 7.9, p = .009, $\eta_p{}^2$ = 0.53]. The analysis of the interaction showed a main effect of Outcomes [F (1,28) = 13.26, p = .001, $\eta_p{}^2$ = 0.69] only in the CP region. In the DOP condition, there was a larger P300/PSW amplitude (mean = 1.5 μV, SD = ± 0.48) than in the NOP condition (mean = −1.0 μV, SD = ± 0.48) (see Fig. 3). In fact, a prominent P300/PSW deflection was absent in the NOP condition. No other significant effects nor interactions were found (ps > .05).

We also found a positive correlation between behavioral performance (accuracy) and CP ERPs (r = 0.64, p = .01) in the DOP condition (see Fig. 4), but not in the NOP condition (r = 0.05, p = .82). The Fisher's Z transformations showed that the difference between the correlation in both conditions was significant [Z = 1.71, p = .04].

3.2.2.2. Late PSW and NSW. Time window from 2400 to 6000 ms after initial stimulus onset (delay period; 1400 to 5000 ms after the initial stimulus offset). The ANOVA revealed a significant main effect of Outcomes [F (1,28) = 20.7, p < .001, $\eta_p{}^2$ = 0.43] and Caudality [F (1,28) = 4.6, p = .041, $\eta_p{}^2$ = 0.14]. The DOP condition showed greater activity (mean = 1.13 μV, SD = ± 0.43) than the NOP condition (mean = −.84 μV, SD = ± 0.43). The CP regions was more active (mean = .5 μV, SD = ± 0.33) than the FC region (mean = −.21 μV, SD = ± 0.33) No other main effect nor interaction were found (ps > .05).

Despite the fact that the interaction Outcomes x Caudality was not significant [F (1,28) = 0.01, p = .98, $\eta_p{}^2$ = 0.01], for theoretical reasons, we test the PSW and the NSW in the CP region and in the FC region, respectively. The analyses showed a main effect of Outcomes in the CP region [late PSW, F (1,28) = 13.17, p = .001, $\eta_p{}^2$ = 0.32] and in the FC region [NSW, F (1,28) = 10.14, p = .004, $\eta_p{}^2$ = 0.27]. A negative slow wave was observed in both regions just in the NOP

Table 1
Mean voltage data (in μV) for the different ERP components (standard deviations in brackets), grouped by outcomes condition (DOP, differential outcomes; NOP, non-differential) and region of interest (ROI: FC, fronto-central; CP, centro-parietal). Time zero starts from initial stimulus onset. (*) represents ERP data statistically similar to zero value (baseline) calculated by Bayesian *t*-Tests. The main significant results from ANOVAs on ERPs amplitudes, f: effect size as well as those from Pearson correlation coefficient, P (N = 15), p (significance in brackets after Bonferroni correction) are included. PSW: positive-slow wave. NSW: negative-slow wave. CNV: contingent negative variation.

Phase	ERP component	ROI	Time window (ms)	DOP	NOP	ANOVAs				Correlation's coefficient (ERP-accuracy)	
						Effect	F	p	f	P (p) DOP	P (p) NOP
Encoding	N200 (i)	FC	250–350	0.58 (0.32)	2.5 (0.32)	Outcomes	17	< 0.001	0.78	(> 0.05)	(> 0.05)
	P300 (i)	CP	350–550	3.6 (0.55)	2.5 (0.55)	Outcomes	9.1	0.005	0.58	(> 0.05)	(> 0.05)
Maintenance	P300 (ii) or Early PSW	CP	1350–1750	1.49 (0.48	−1.01 (0.48)	Outcomes	13,26	001	0.69	0.64 (0.01)	(> 0.05)
	Late PSW	CP	2400–6000	1.3 (0.34)	−0.49* (0.34)	Outcomes	13.2	0.001	0.69	0.58 (0.01)	–
	NSW	FC	2400–6000	0.75* (0.44)	−1.2 (0.44)	Outcomes	10.1	0.004	0.61	–	(> 0.05)
Retrieval	N100	CP	6150–6250	−0.1 (0.22)	−1.27 (0.22)	Outcomes	6.5	0.033	0.56	0.53 (0.03)	(> 0.05)
	N200 (ii)	FC	6250–6350	−0.11 (0.84)	1.1 (0.84)	–	(> 0.05)			(> 0.05)	(> 0.05)
	P300 (iii)	CP	6350–6550	5.2 (0.55)	2.4 (0.55)	Outcomes	12.2	0.001	0.67	0.75 (0.001)	(> 0.05)
	CNV	FC	6700–8000	−0.41 (0.52)	0.38 (0.52)	–		(> 0.05)		–	–

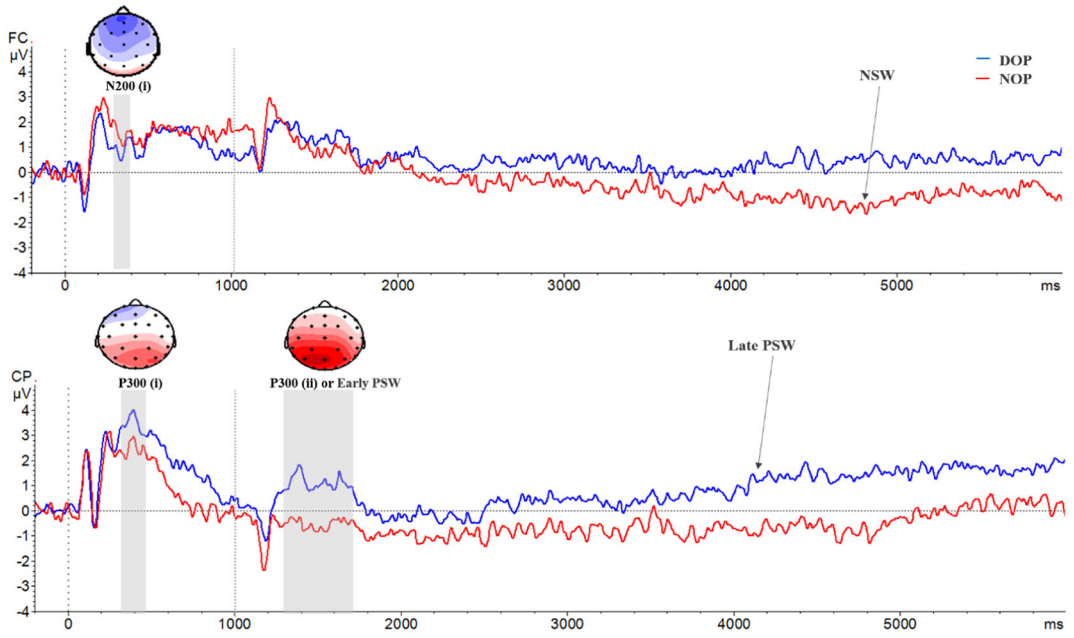

Fig. 3. Panel A. On the bottom, grand-average voltage data (in μV) of ERP in the fronto-central region (FC: average of F3, FC1, FC5, F4, FC2 and FC6) as a function of Outcome (differential –DOP, blue line, vs. non-differential –NOP, red line). Grey shades represent the N200 time windows for the i) encoding phase. On the top, topographic map of the difference in ERP waves between Outcomes condition (DOP–NOP) in each N200 time window. NSW: Negative-Slow Wave. Panel B. Grand-average voltage data (in μV) of Centro Parietal (CP: average of C3, CP1, P3, P7, P4, C4, CP2, P4, P8) signals as a function of Outcomes (differential –DOP, blue line - vs. non-differential –NOP, red line). Grey rectangular shades represent the P300 time windows for i) the encoding phase, and ii) the delay period. On the top, topographic map of the difference in ERP waves between Outcomes condition (DOP–NOP) in each P300 time window. PSW: Positive-Slow Wave. Time zero represents initial stimulus onset. Delay period between vertical dotted lines from 1000 to 6000 ms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

condition (Late PSW, CP-.49 μV; NSW, FC: −1.2 μV). By contrast, in the DOP condition a positive slow wave was obtained also in both regions (Late PSW, CP:1.3 μV; FC:.35 μV;). No other significant effects nor interactions were found (ps > .05).

Once more, accuracy in the DOP condition correlated significantly with late PSW amplitude only in the CP region (r = 0.58, p = .02) (see Fig. 4). There was no statistically reliable correlation in the NOP condition (r = 0.01, p = .73). The Fisher's Z transformations showed that the difference between the correlation in both conditions was significant [Z = 1.6, p = .05].

Table 2 summarizes the estimated Bayes factors (BF_{10}) obtained when comparing ERPs signals in each time window under study and the baseline, in each Outcomes condition. The Bayesian analyses were performed using SPSS version 25.0 (IBM Corp, 2017).

3.2.3. Retrieval phase (voltage data corrected to a 200 ms baseline before the onset of the comparison stimuli)

3.2.3.1. N100. Time window from 6150 to 6250 ms after initial stimulus onset (150–250 ms after comparison stimuli onset). The ANOVA revealed a significant interaction effect of Outcomes x Caudality [F (1,28) = 5.12, p = .032, η_p^2 = 0.16]. The analysis of this interaction revealed a significant main effect of Outcomes [F (1,28) = 6.54,

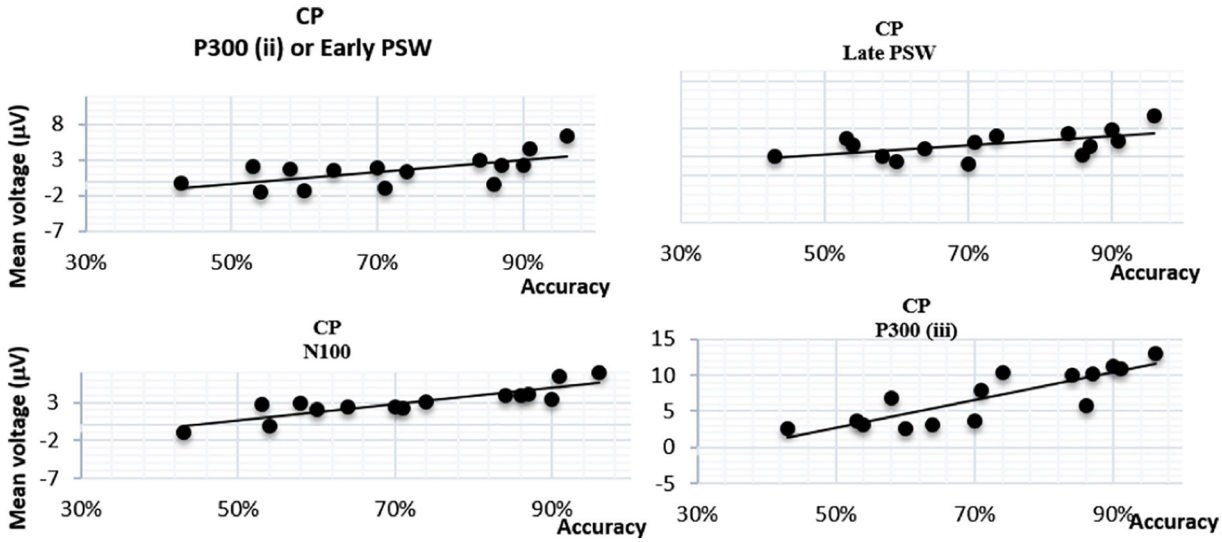

Fig. 4. Relationship between mean voltage (in mV) in centro-parietal regions (CP) and accuracy in the DOP condition in: the (a) P300 (ii) or Early PSW and Late PSW time windows in the delay period; and (b) N100 and P300 (iii) time windows in the retrieval phase.

Table 2
Bayes factor obtained by comparing the electrical activity in each subinterval (200 ms) with the baseline by region of interest and Outcomes condition. Simple asterisk means moderate evidence, double asterisk, strong evidence, and triple asterisk, very strong or extreme evidence to accept the Null hypothesis (H0) or the Alternative hypothesis (H1) (Lee and Wagenmakers, 2013).

Late PSW-NSW time window	Bayes factor			
	CP region		FC region	
	DOP	NOP	DOP	NOP
2600	10*	,196*	,135*	2,5
2800	5*	,833	,120*	5*
3000	20**	,909	,161*	2
3200	1000***	,667	,128*	10*
3400	1000***	,238*	,098**	5*
3600	> 1000***	,149*	,106*	10*
3800	500***	,199*	,093**	20**
4000	> 1000***	,070**	,090**	20**
4200	> 1000***	,098**	,098**	1000***
4400	500***	,089**	,069**	1000***
4600	500***	,078**	,083**	> 1000***
4800	> 1000***	,108*	,123*	100**
5000	> 1000***	,066**	,106*	10*
5200	> 1000***	,123*	,103*	50**
5400	333***	,185*	,192*	100**
5600	1000***	,161*	,244*	10*
5800	> 1000***	,139*	,217*	10*
Accepted Hyp.	H1	H0	H0	H1

$p = .033$, $\eta_p^2 = 0.24$] just in the CP region; in fact, potentials were positive in the DOP (.12 μV) and negative in the NOP condition (−1.27 μV) (see Fig. 5). No other effects nor interactions were found (*ps* > .05).

We found a positive correlation between accuracy and ERPs at CP electrodes in the DOP condition ($r = 0.53$, $p = .03$) (see Fig. 4). The correlation in the NOP condition was not statistically significant ($r = -0.1$, $p = .52$). The Fisher's Z transformations revealed significant differences between the correlations in both conditions [$Z = 1.69$, $p = .045$].

3.2.3.2. N200 (ii). Time window from 6250 to 6350 ms after the initial stimulus onset (250–350 ms after comparison stimuli onset). The ANOVA revealed a significant main effect of Caudality [F (1,28) = 16.2, $p < .001$, $\eta p^2 = 0.37$] and Laterality [F (1,28) = 7.1, $p = .013$, $\eta p^2 = 0.20$] due to a greater activity in the CP region (mean = 3.5 μV, SD = ± 0.45) than in the FC regions (mean = 1.7 μV, SD = ± 0.45) and to the left hemisphere being more active (mean = 3.1 μV, SD = ± 0.34) than the right (mean = 2.19, SD = ± 0.34). The Outcome × Caudality interaction effect also reached significance [F (1,28) = 4.4, $p = .047$, $\eta p^2 = 0.13$]. The analysis of the interactions Outcome × Caudality did not reveal significant main effect of Outcomes in either of the two regions [FC: F (1,28) = 2.15, $p = .15$, $\eta_p^2 = 0.07$; CP: F (1,28) = 0.1, $p = .77$, $\eta_p^2 = 0.003$]. In spite of this, it is important to emphasize that the N200 (ii) was registered only in the FC region, and that it was negative in the DOP (−.11 μV) and positive in the NOP (1.1 μV) (see Fig. 5). No other main effect was found (*ps* > .05).

3.2.3.3. P300 (iii). Time window from 6350 to 6550 ms after the initial stimulus onset (350–550 ms after the comparison stimuli onset). The ANOVA showed significant main effects of Outcomes [F (1,28) = 16.6, $p < .001$, $\eta p^2 = 0.37$] and Caudality [F (1,28) = 36.4, $p < .001$, $\eta p^2 = 0.77$]. That is, the activity registered in the DOP condition was greater (mean = 3.9 μV, SD = ± 0.43) than in the NOP condition (mean = 1.4 μV, SD = ± 0.43), and the FC region showed lower activity (mean = .46 μV, SD = ± 0.72) than CP region (mean = 4.8 μV, SD = ± 0.72). The Outcomes x Caudality interaction was again significant [F (1,28) = 4.4 $p < .04$, $\eta p^2 = 0.14$] due to a significant main effect of Outcomes [F (1,28) = 12.23, $p = .001$, $\eta p^2 = 0.31$] only in the CP region. Potentials (see Fig. 4) were more positive in the DOP (5.2 μV) than in the NOP condition 2.4 μV). No other significant effects nor interactions were found (*ps* > .05).

There was a significant correlation between accuracy and ERP signals in this interval in CP region ($r = 0.75$, $p = .001$) only in the DOP condition (see Fig. 4). There was no significant correlation in the NOP condition ($r = -0.16$, $p = .57$). The Fisher's Z transformations showed

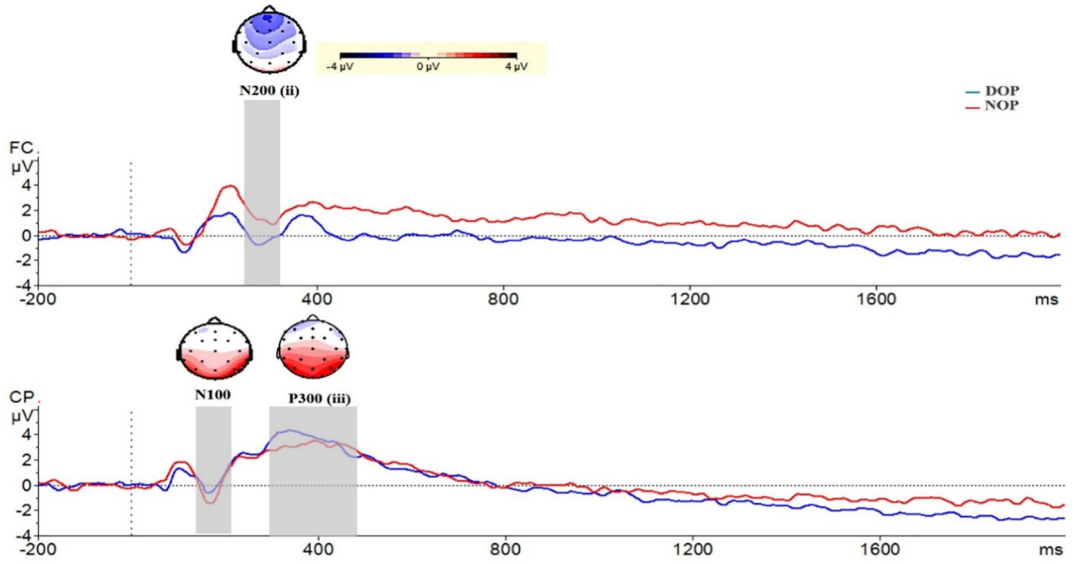

Fig. 5. Panel A. On the bottom, grand-average voltage data (in μV) of ERP in the fronto-central region (FC: average of F3, FC1, FC5, F4, FC2 and FC6) as a function of Outcome (differential –DOP, blue line, vs. non-differential –NOP, red line). Grey shades represent the N200 time windows for the ii) retrieval phase. On top, topographic map of the difference in ERP waves between Outcomes condition (DOP–NOP) in N200 time window. Panel B. Grand-average voltage data (in μV) of Centro Parietal (CP: average of C3, CP1, P3, P7, P4, C4, CP2, P4, P8) signals as a function of Outcomes (differential –DOP, blue line - vs. non-differential –NOP, red line). Grey rectangular shades represent the P300 (iii) time windows for the retrieval phase. On top, topographic map of the difference in ERP waves between Outcomes condition (DOP–NOP) in each time window. Time zero start from comparison stimulus onset (vertical dotted line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that the difference between the correlations in both conditions was significant [$Z = 2.78$, $p = .002$].

3.2.3.4. CNV. Time window from 6700 to 8000 ms after the initial stimulus onset (700–2000 ms after the comparison stimuli onset). The ANOVA did not reveal significant main effects nor interactions (ps $> .05$).

4. Discussion

To date, very few studies investigated the neural and cognitive mechanisms underlying the DOP in humans (Carmona et al., 2019a,b; Mok, 2012; Mok et al., 2009). The DOP establish a situation, in which specific consequences of our responses can be predicted. The main aim of this study was to further elucidate the mechanisms underlying the DOP in visual short-term memory by determining the time course of brain activation using ERPs. As expected, the behavioral results provide evidence regarding the positive effects of the DOP on visual short-term memory. Specifically, it was observed that this procedure improved memory recall of complex visual information in healthy young adults.

Concerning the electrophysiological correlates of the DOP, our hypothesis was that differences in the ERP signals would be observed in all the three phases of the short-term memory task (encoding, maintenance and retrieval) as a function of how the outcomes were administrated (differential or non-differentially). According to both expectancy theory and two-memory systems theory, once the association between the target stimulus and its specific outcomes is established, an internal representation of the unique outcomes would remain active during the delay in the DOP condition. By contrast, only the representation of the initial stimulus would be activated during this period when non-differential outcomes were used (NOP condition). In addition, our hypothesis was also based on previous research indicating that i) the stimuli-reward association enables the encoding of visual information (Gong and Li, 2014; Infanti et al., 2015) and ii) the stimuli associated with specific outcomes capture attention involuntary (Anderson et al., 2011a,b, 2014). Attentional capture should decrease interference from distractor stimuli (Kuo et al., 2012; Zanto and Gazzaley, 2009), particularly in the retrieval phase of a DMST, in which there are several distractors presented along with the target stimulus.

In line with our hypothesis, during the *encoding phase*, there were differences between the DOP and NOP conditions in two ERPs components, N200 (i) and P300 (i), that have been related to reward expectancies in the cue-evaluation stage. On the one hand, a larger N200 was observed in the DOP condition compared with the NOP condition. The fronto-central N200 is modulated by reward-related stimuli (e.g., Novak and Foti, 2015; Potts, 2011) and the largest amplitude is usually associated with: i) an increase in cognitive control (Näätänen and Picton, 1987; Potts, 2011), ii) an increase in mental-template mismatch stimulus-expectancy (Donkers et al., 2005) and iii) an internal (memory) readout of a repetitive stimulus expected that has been omitted in that moment (Simson et al., 1976; Picton et al., 1974). Given that after several pairings, the presentation of the initial stimulus would activate the representation of its associated unique outcomes, the larger N200 in the DOP condition could reflect both increased recruitment of cognitive control mechanisms or a memory readout of the repetitive stimuli expected (the initial stimulus -on screen- and its unique outcome associated -omitted-).

The centro-parietal P300 component was also modulated by outcome expectancies. This ERP component has been linked to stimulus probability (Polich, 2007) and stimulus categorization processes. Furthermore, a larger P300 amplitude is obtained for reward cues (Hughes et al., 2013). Our results showed a significantly larger amplitude in the DOP than in the NOP condition. Although in both conditions rewards expectancies can be formed, this effect might reflect the fact that only the DOP allows to establish specific expectancies of the unique outcome associated with the target stimulus. This appears to greatly affect the encoding processes.

Importantly, during the delay period (*maintenance phase*), when no stimuli are presented, we expected to find ERP differences in the two experimental conditions. According to the theoretical explanations of the DOP and two recent human studies (Carmona et al., 2019a,b; Mok, 2012), an internal representation of the initial stimulus should be maintained over the delay (a retrospective process) to correctly solve the task in the NOP condition. By contrast, an additional source of information, a representation of the unique outcome (prospective process), would remain active when differential outcomes are expected. In line with these hypotheses, only in the NOP condition negative slow waves were observed specially in FC regions in the second half of the delay (2400–6000 ms), whereas the ERPs in the DOP condition in this region was similar to the baseline. Such fronto-central negative slow waves have been found under conditions of visual working memory maintenance (Kuo et al., 2012; Mecklinger and Pfeifer, 1996; Ruchkin et al., 1990, 1992). In contrast in the DOP condition, a late centro-parietal positive slow wave was obtained in the same time period, whereas the ERPs in the NOP condition in this region was similar to the baseline. Centro-parietal positive slow waves are typically elicited when processing the outcome after the feedback display (Novak and Foti, 2015; Pornpattananangkul and Nusslock, 2015; Ruchkin et al., 1995). In addition, an enlarged P300 (ii) and more pronounced early PSW were observed only in the DOP condition. These components are typically elicited by stimuli associated with reward (Glazer et al., 2018).This suggests that the target stimulus triggers the representation of the expected outcome, which in turn evokes ERP component related to reward processing.

After the comparison stimuli onset (*retrieval phase*), a N100 component significantly of greater amplitude in the NOP than in the DOP condition was registered in CP regions (Downing, 2000; Olivers, 2007; Zanto and Gazzaley, 2009). The N100 component may relate to control mechanisms involved in reducing the interference from distractor stimuli, a top-down control process or endogenous attention modulated by expectancies in such a way that the higher expectancies, the lower amplitudes in this component (Kuo et al., 2012; Zanto and Gazzaley, 2009). In this phase, a N200 (ii) component more negative in the DOP than in the NOP was registered only in FC regions, although this difference did not reach significance. In addition and as expected, the CNV registered over the FC region, was similar in both the NOP and in DOP conditions. This negative wave is associated with the recruitment of attentional and perceptual anticipatory processes (Glazer et al., 2018; Gómez et al., 2007). Taken as a whole, these results suggest that in the NOP condition the activated attentional resources are not enough to correctly solve the task. Furthermore, the P300 (iii) component that followed the N100 in CP regions, was found in both outcomes conditions with a significantly greater amplitude in the DOP than in the NOP condition. It should be mentioned that a smaller amplitude in P300 has been usually related to the processing of stimuli difficult to discriminate (Näätänen and Picton, 1987).

Finally, in the DOP condition, amplitudes of several ERP components were positively related to accuracy: Better performance was associated with: (i) increased amplitudes of the P300 (ii), early PSW, late PSW and P300 (iii); and decreased amplitudes of the N100 to the comparison stimulus. These findings indicate evidence that amplitudes of the components were related to improved performance in this outcome condition. In contrast, behavioral performance in the NOP condition was not related to the amplitude of either of the ERP waves analyzed: N200 (i), P300 (i), NSW, N100 and P300 (iii). Thus, these components do not reflect efficacy of task performance in the NOP condition.

In conclusion, this study addresses for the first time the temporal course of cognitive processes involved in the DOP effect. As previously mentioned (Carmona et al., 2019a,b), the way the brain processes the information seems to change to a prospective manner when differential outcomes are arranged. Accordingly, the present results indicate that when the association between the target stimulus and its specific

outcome is established, a representation of the expected outcome is activated by the presentation of the stimulus to be encoded and is maintained during the delay period, as demonstrated by the ERPs components (P300 (ii), Early PSW and late PSW) observed in the CP region only under the DOP condition. In contrast, in the NOP condition, we observed a NSW component usually associated with working memory maintenance. Hence depending on the arrangement of the outcomes (differential vs. non-differential) different memory processes are involved (prospective vs. retrospective). These finding support the two-memory systems theory of the DOP effect by demonstrating that the training with this procedure affects encoding, maintenance and retrieval phases. Specifically, the DOP appears to increase cognitive control in the encoding phase as well as seems to enhance discrimination of the stimuli in the retrieval phase by reducing attentional resources.

Declaration of competing interest

The authors report no conflicts of interest.

Acknowledgements

This research was supported by Grants PSI2015-65248-P and PSI2017-83135-P from the Spanish Ministry of Economy and Competitiveness, co-funded by ERDF (FEDER) funds and Grant PID2019-110066GB-I00 from the Spanish Ministry of Science and Innovation, co-funded by ERDF (FEDER) funds. IC was supported by a pre-doctoral grant by the Ministry of Education, Culture and Sports (FPU2014-03091).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijpsycho.2020.06.010.

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