Implicit outcomes expectancies shape memory process: Electrophysiological evidence

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ARTICLE INFO

ABSTRACT

The simple manipulation of pairing specific outcomes with the sample stimuli strongly affects discriminative learning and memory processes. This procedure has been named the Differential Outcomes Procedure (DOP) and is usually compared to a control condition (the non-differential procedure, NOP) consisting in the random administration of the outcomes after each correct response. Recent research has revealed that the DOP effect arises even under unconscious conditions. In this study, we explored the temporal dynamics of short-term memory processes in both the DOP and the NOP in the absence of awareness of either the outcome (Experiment 1A) or the initial sample stimulus (Experiment 1B) through the evoked-related potentials technique. Results showed distinctive electrophysiological activation patterns in the DOP compared with the NOP at encoding, maintenance and retrieval phases. The present findings provide electrophysiological evidence of implicit-prospective processes involved in the DOP. They elucidate the processes that result in improved visual recognition memory.

1. Introduction

The simple manipulation of pairing specific outcomes with the target (or sample) stimuli strongly affects discriminative learning and memory processes in human and animal studies (for a review, see McCormack, Elliffe, & Virues-Ortega, 2019; Mok, Estevez, & Overmier, 2010; Urcuioli, 2011). This procedure has been named the Differential Outcomes Procedure (DOP) and is usually compared to a control condition (the non-differential procedure, NOP) consisting in the random administration of the outcomes after each correct response. That is, correct responses to a sample stimulus (e.g., a blue square) are always followed by a specific and unique outcome (e.g., the picture of a smiling baby) in the DOP, while in the NOP all correct responses are rewarded by a randomly selected outcome (e.g., the picture of a smiling baby or the picture of a sunset).

Recent studies have revealed that the effect of the DOP arises even implicitly (without the participants' intention, see Martínez-Pérez, Fuentes, & Campoy, 2019), or under unconscious conditions (Carmona,

Marí-Beffa, & Estévez, 2019). For instance, superior visual short-term memory was observed when this procedure was used regardless of the awareness (subliminal or supraliminal presentation) of the specific outcomes or the sample stimulus, via an implicit-prospective memory process (Carmona et al., 2019). Therefore, the explicit knowledge of such stimuli (the outcome or the initial sample stimulus) appears not to be a necessary condition for observing DOP beneficial effects on discriminative learning and memory. This finding has important implications in revealing relevant applications of the differential outcomes methodology at different stages of the human brain development, as well as in improving memory and learning performance in patients that exhibit conscious processing, explicit memory, or executive functions impairments (e.g., those populations with neurodegenerative diseases or neurodevelopmental disorders). Furthermore, the results from the Carmona et al.'s (2019) study are in agreement with the two-memory systems model (Savage & Ramos, 2009; Savage, Pitkin, & Careri, 1999; Savage, 2001; Savage, Buzzetti, & Ramirez, 2004), which received considerable empirical support. This theory suggests that, in the

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differential outcomes condition, after several initial sample stimulus-specific outcome pairings, expectancy of this unique outcome is implicitly formed via classical conditioning associations so that, when the initial sample is displayed, a representation of its specific outcome (a prospective memory process) would be activated in an automated and non-intentional way. This outcome representation would remain active during the delay, being used as an additional source of information to select the correct choice. On the other hand, when the task is carried out under the NOP, participants can only complete the task correctly if they are actively remembering the initial sample stimulus (a retrospective memory process).

Two follow-up studies have been conducted in our lab to further support, at the neural level, Carmona et al.'s (2019) behavioral findings by using a psychophysiological approach. In the first study, Carmona, Ortells, Kiefer, and Estévez (2020) measured evoked-related potentials (ERP) to disclose the brain activation patterns that underlie the aforementioned two memory processes, prospective and retrospective, associated to the DOP and the NOP, respectively. For that study, both the sample stimulus and the outcome were presented visibly. Differential ERPs were found at the three phases involved in the short-term memory process (encoding, maintenance, and retrieval) depending on whether the DOP or the NOP was implemented. For instance, a positive-slow wave (PSW) observed in centro-parietal (CP) regions during the delay period (maintenance phase) was observed with the DOP. That is, the internal representation of the implicitly anticipated outcome (or expectancy) when the initial sample stimulus was displayed, elicited the same ERP component that is usually found when the outcome is processed after the feedback display (Glazer, Kelley, Pornpattananangkul, Mittal, & Nusslock, 2018; Novak & Foti, 2015; Pornpattananangkul & Nusslock, 2015). In contrast, a negative-slow wave (NSW) was obtained in fronto-central (FC) regions during the same period, when participants performed the task under the NOP. This negative wave, involved in keeping active visual information in working memory (Kuo, Stokes, & Nobre, 2012; Mecklinger & Pfeifer, 1996; Ruchkin, Johnson, Canoune, & Ritter, 1990; Ruchkin, Johnson, Grafman, Canoune, & Ritter, 1992; Ruchkin, Canoune, Johnson, & Ritter, 1995), was associated with the maintenance of an internal representation of the initial sample stimulus, a retrospective process. Further differences in ERPs components between the DOP and the NOP were also found at both encoding and retrieval memory stages (see Carmona et al., 2020, for more details).

In the current second follow-up study, we used the same procedure as in the Carmona et al.'s (in press) study, but with either the outcomes (Experiment 1A) or the initial sample stimuli (Experiment 1B) presented outside awareness. Here we asked whether the same pattern of brain activation observed with supraliminal stimulus presentations are also obtained with subliminal stimulus presentations, replicating, at the neural level, the results of Carmona et al. (2019) at the behavioral level. Note that by replicating the dissociation between the DOP and the NOP at both the behavioral and neural levels, under both supraliminal and subliminal conditions, would reinforce the implicit nature of associative processes involved in learning and memory under differential outcomes procedures.

On the basis of our previous ERP study (Carmona et al., 2020), distinctive electrophysiological activation patterns should emerge in the DOP compared with the NOP at encoding, maintenance and retrieval phases. A P300 component with higher amplitude with the DOP than with the NOP is expected in CP regions at both encoding and retrieval (Holroyd, Krigolson, & Lee, 2011; Hughes, Mathan, & Yeung, 2013; Novak & Foti, 2015; Pornpattananangkul & Nusslock, 2015; Ruchkin et al., 1995). During the maintenance phase (delay period), a PSW is also expected at CP regions just with the DOP, whereas a NSW is expected in FC regions just with the NOP. These results should be found irrespective of whether it is the outcome associated with the correct response (Experiment 1A) or the initial sample stimulus (Experiment 1B), that is presented subliminally (Carmona et al., 2019; Mok, 2012).

2. Experiments 1A and 1B

2.1. Method

2.1.1. Participants

Sixty-three undergraduates from the University of Almería (Spain) volunteered to participate in the study in exchange of course credit. Thirty one (9 males and 22 females) participated in Experiment 1A (ranging in age from 18 to 35 years, $M = 23.8$, $SD = 3.1$), and the rest (11 males and 21 females) in Experiment 1B (ranging in age from 18 to 32 years, $M = 22.4$, $SD = 3.5$). They were randomly assigned to one of the two experimental outcome conditions, DOP and NOP. Participants in the two outcomes conditions were matched regarding age, sex, and education level. Written informed consent was signed for each participant and all of them reported normal or corrected-to-normal vision. They received extra course credit for their participation and the chance to win one of the prizes that were raffled off at the end of the study. Participants were unaware of the purposes of the experiments. This study was approved by the University of Almería Bioethics Committee in Human Research, and was conducted in accordance with the ethical protocols and recommendations of the "Code of Good Practices in Research" of this committee and with the Declaration of Helsinki.

2.1.2. Setting and materials

Stimulus presentation and data collection (accuracy and latency) were controlled by the E-prime software (Psychology Software Tools, 2012). Participants were tested individually in the same quiet room, with identical sound and lighting conditions.

The stimuli were white circular shapes with shaded sectors (see Fig. 1), and were identical in shape, color, and size ($3° \times 3°$ of visual angle) to those used in previous studies (Carmona et al., 2019, in press). They were displayed on a black background on a color monitor (15-inch VGA monitor) of an IBM/PC compatible computer. The sample stimulus was presented at the center of the screen, and the six comparison stimuli were displayed in a 2×3 grid. Four initial sample stimuli and the same four reinforcers (a pendrive, a five-euro bill, a key ring, or a set of four pens) to those employed in the two aforementioned studies, were used in Experiment 1A, and two sample stimuli and two reinforcers (a pendrive and a key ring) in Experiment 1B. After each correct choice, a black and white photo of the prizes 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. The phrases were in Courier New, size 12 and in white color. The reinforcers were raffled off at the end of the study.

2.1.3. Procedure

All participants performed a recognition memory task, lasting approximately 17 min, which consisted of four practice trials followed by 96 experimental trials, grouped in two blocks of 48 trials each. The order of the two blocks of trials and the position of the correct comparison stimulus on the screen were counterbalanced across participants. In the DOP, each initial sample stimulus was always associated with a unique outcome so that each correct choice of a particular comparison stimulus was always followed by its specific outcome. In the NOP, correct responses were also followed by the same outcomes used in the DOP, but outcomes were presented in a random manner although all of them were used with equal frequency as in the DOP.

In Experiment 1A, the instructions were the same that those used in previous studies (Carmona et al., 2019). They were explained verbally and were also written on the screen: "First, a central fixation point will appear. Then, it will be replaced by a circular shape presented for a short time. You must pay attention because, after a short delay, you will have to identify the shape that you have just seen out of six different options by clicking on it with the mouse as quickly as possible. When you are ready, please press the space bar to begin". Participants were informed that (i) a masked outcome would appear after their correct choice (see
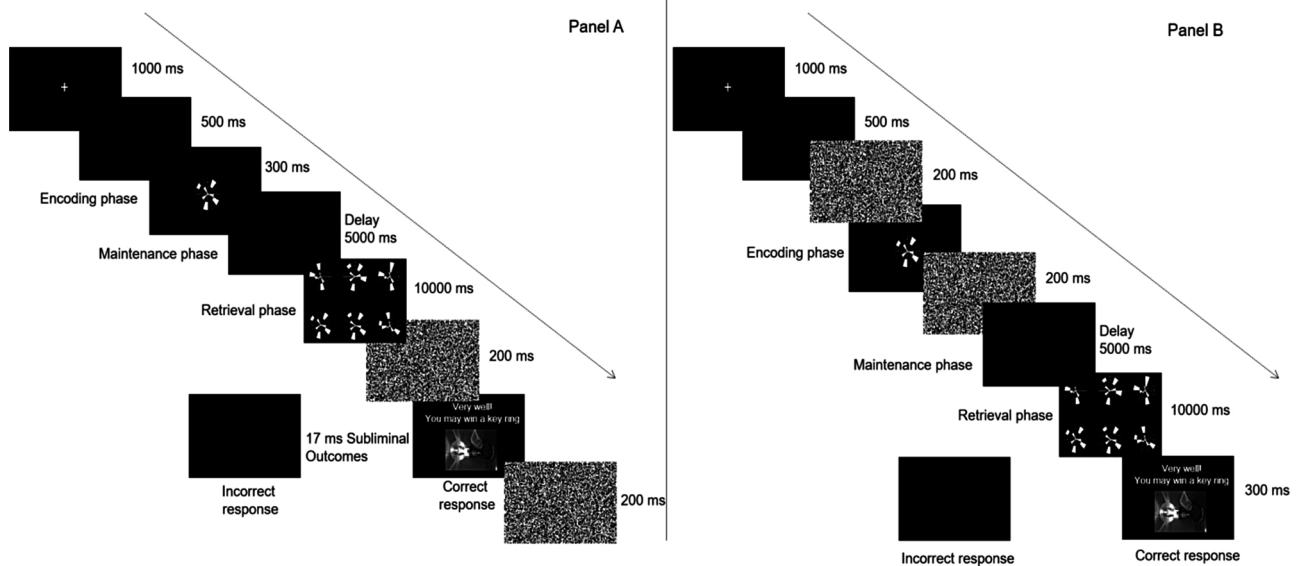
Fig. 1. Stimulus sequence (from left to right) used in experiments 1A (panel A) and 1B (panel B).

Fig. 1, panel A); (ii) even when they could not see it, the outcome for the correct response would include a picture of one of the four prizes, whereas incorrect choices would be followed by a blank screen; (iii) the reinforcers would be raffled off at the end of the study; and, (iv) the more accurate their responses were, the more tickets they would win for the raffle with higher chances of winning one of the prizes.

Each trial began with a fixation cross presented for 1000 ms (see Fig. 1, panel A). After a blank brief period of 500 ms, a circular shape was displayed for 300 ms followed by a delay of 5000 ms (blank screen). Then, six comparison stimuli (the sample stimulus plus five distractor shapes) appeared and remained on the screen until the participants responded by clicking on one of the shapes with the left mouse button, or 10 s were elapsed, whichever occurred first. The position of the comparison stimulus that matched the previously presented sample stimulus was counterbalanced. When the response was correct, the specific outcome was presented during 17 ms between two pattern masks that appeared for 200 ms before and after the outcome. When the response was incorrect, the screen remained blank during the same time used for the outcome presentation. The trial was also scored as incorrect if the participant did not emit any response in 10 s.

In Experiment 1B, the procedure was similar to that used in the Experiment 1A except that now the sample stimulus instead of the outcome was presented subliminally (17 ms) and interposed between two pattern masks that appeared for 200 ms (before and after the sample stimulus; see Fig. 1, panel B). In addition, instructions were modified so that participants were asked to choose, as quickly as possible, the comparison stimulus (the shape) they guessed it matched the previously masked sample stimulus, even if they had not seen any shape during the sample stimulus display. They were also informed that when their responses were correct, they would see a picture of a prize, whereas the screen would remain blank for several seconds if the response was incorrect. The outcome was displayed on the screen for 300 ms after the correct response. Two sample stimuli and two outcomes, instead of four, were used although the total number of trials remained the same as in Experiment 1A. The reason for such decision is that in previous pilot studies, we had observed that masking the sample stimulus, instead of the outcome, increased the difficulty of the task up to the point of participants performing close to chance. Thus, to foster participants' accuracy, for the current experiment we reduced from four to two the sample stimuli, and consequently the outcomes (see also Carmona et al., 2019).

At the end of the experiments, each participant had to report whether they had perceived anything in the outcome display (Experiment 1A) or any shape in the sample stimulus display (Experiment 1B). Three of them (one in Experiment 1A and two in Experiment 1B) reported to have perceived the masked stimulation, and consequently their data were excluded from the statistical analyses, although none of them could identify any specific shape/image.

Although in the Carmona et al.'s (2019) study was clearly demonstrated that the conditions of stimulus presentation, similar to the ones used here, were indeed subliminal, we tested participants' stimulation visibility with a discriminative decision task at the end of the two experiments. Eight circular or square sample stimuli were displayed subliminally on the screen (17 ms interposed between two pattern masks that appeared for 200 ms). Stimuli were repeated twice, so that the total number of trials were 32. Participants had to decide whether they had seen either a circular shape or a squared shape by pressing keys 1 or 2 on the keyboard (response keys assigned to the two types of shapes were counterbalanced across participants). Participants were informed that there was the same number of circular and squared shapes. All of them performed close to the chance level [t_{1A} (29) = .5, p = .48; t_{1B} (29) = .3, p =.54].

2.1.4. Data recording and processing

The electroencephalogram (EEG) was recorded with a 30-channels electrode cap (actiCAP, Brain Products, Munich, Germany) conforming to the standard international 10–10 system of electrode location. The reference channel was located in the midfrontal electrode (FCz). The electrode located between Fpz and Fz served as grounding channel. Two 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 the left eye to record horizontal electrooculogram (HEOG).

Two electrodes were placed on both mastoid areas, right and left, in order to the EEG data being off-line re-referenced. Impedance in all electrodes remained below 5 kΩ. The electrical signals were digitized using an AC-coupled amplifier (Brain Amp, Brain Products, Munich, Germany) 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: .1 Hz, 12 dB/octave attenuation). The BrainVision Analyzer 2.0 software (Brain Products, Munich, Germany) was used for the processing of EEG data.

EEG data were corrected for ocular/blink artifacts through independent component analysis (ICA; Makeig, Jung, Bell, Ghahremani, &

Sejnowski, 1997), the average of components rejected was 2 in Experiment 1A and 3 in Experiment 1B; and after the segmentation to a 200 ms baseline before the onset of the initial sample stimulus (i.e., the last 200 ms of the preceding black screen). Further correction to a 200 ms baseline before the comparison screen onset was conducted in order to analyze EEG data in the retrieval phase.

ERP data were segmented from 200 ms pre-initial stimulus onset to 2000 ms post-comparison screen onset. Trials with incorrect responses were excluded from the segmentation procedure. Response times greater or equal than 2000 ms were included in the analysis. Later on, the artifacts rejection procedure was completed off-line for each EEG channel (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). All artifacts were excluded from averaging and all channels were re-referenced off-line to averaged mastoids before the EEG segments were averaged. The number of averaged segments was greater than 30 (> 30 % of valid trials) in all conditions.

On the basis of previous research about event-related ERPs, as well as in our previous ERP study using the DOP (Carmona et al., 2020), fronto-central (FC) and centro-parietal (CP) regions of interest (ROI) were examined in order to explore P250, P300 and PSW (Chapman, Gardner, Mapstone, Dupree, & Antonsdottir, 2015; Novak & Foti, 2015; Pornpattananangkul & Nusslock, 2015; Ruchkin et al., 1995), and N100, NSW and CNV (Kuo et al., 2012; Ruchkin et al., 1990; Zanto & Gazzaley, 2009) components.

Consequently, six FC and six CP electrodes, grouped by hemisphere, were used for the EEG analyses (F3, FC1 and FC5, conforming the FC-left region; F4, FC2, and FC6, conforming the FC-right region; C3, CP1, and P3 conforming the CP-left region; and C4, CP2, and P4 conforming the CP-right region). In addition, two medial fronto-central (mFC; Fz and FCz), and two medial centro-parietal (mCP; Cz and Pz) electrodes were also selected. As additional analysis, we conducted *t*-tests between the DOP and NOP conditions at each electrode (see supplementary material). The following time windows (in ms) were chosen to assess the ERP components: (i) for the encoding phase, 200–300 after the sample stimulus onset; for the maintenance phase, 0–200, 200–1000, 1000–2000, and 2000–5000 after the delay onset; and for the retrieval phase, 150–250, 300–700 and 700–1700 after the comparison stimuli onset.

2.1.5. Statistical analyses

Behavioral data (accuracy and correct response latency) were submitted to a 2 × 2 × 2 mixed analysis of variance (ANOVA) with Experiment (1A and 1B) and Outcomes (DOP and NOP) as the between-participants factors, and Blocks (Block 1 and Block 2) as the within-participants factors.

Although we observed a significant Outcomes x Block interaction in accuracy data, the effect of Outcomes was statistically significant in the two blocks of trials, and therefore the factor Block was not included in the EEG analyses. Thus, electrophysiological data were analyzed through mixed 2 × 2 × 2 × 3 ANOVAs with Experiment (1A and 1B) and Outcomes (DOP and NOP) as the between-participants factors; and Caudality (FC and CP) and Laterality (Left hemisphere, Medial line, and Right hemisphere) as the within-participants factors, in all the time windows under study.

Kolmogorov-Smirnov, and Levene's tests were conducted to check normality of data and homogeneity of variance, respectively. Results showed normal distributions and homogeneity of variance in all variables. Bonferroni correction was applied to correct for type I error accumulation in multiple comparisons.

2.1.5.1. Bayesian analyses.
Bayesian factors were estimated in order to identify the probability of finding significant differences between ERPs signals in the slow long latency waves time window under study (Late

PSW-NSW) and baseline (zero value) in the ROIs for both Outcomes conditions.

2.1.5.2. Correlation analyses.
Pearson's correlation coefficient was used in all correlation analyses. Linear regression analyses were conducted to assess the relationship between performance (accuracy and reaction times) and ERP activity in the ROIs, in each time window. Only significant correlations ($ps < .05$) are shown.

3. Results

3.1. Experiments 1A (subliminal outcomes) and 1B (subliminal sample stimulus)

3.1.1. Behavioral results (accuracy and latency)
The analysis of correct responses (see Fig. 2) showed main effects of both Experiment [F (1,56) = 7.3, p = .009, η_p^2 =.12] and Outcomes [F (1,56) = 38, $p < .001$, η_p^2 =. 41], indicating that participants were less accurate in Experiment 1B (48 %) than in Experiment 1A (56 %), and in the NOP (43 %) than in the DOP (61 %). The main effect of Block was also significant [F (1,56) = 95.3, $p < .001$, η_p^2 = .61]; performance was worse in the first block than in the second block of trials (46 % vs. 57 %).

There was a significant Experiment x Block interaction [F (1,56) = 9.7, p = .003, η_p^2 =.15]. The analysis of the interaction showed that the difference between blocks was significant in both experiments, although such difference was larger in Experiment 1A than in Experiment 1B (1A: 46 % vs. 57 %, block 1 vs. block 2, t(29) = 8.9 p < .001; 1B: 44 % vs. 52 %, block 1 vs. block 2, t(29) = 4.1 p < .001). The Outcomes x Block interaction was also significant [F (1,56) = 9.2, p = .004, η_p^2 =.14]. The analysis of the interaction revealed that although the Outcomes effect was significant in both blocks of trials (block 1: DOP = 53 %, NOP = 38 %, t(58) = 4.28, p <.001; block 2: DOP = 68 %, NOP = 47 %, t(58) = 6.4, p < .001), the differences were larger in block 2 than in block 1 (see Fig. 2).

The analysis of latency data showed a main effect of Blocks [F (1,56) = 34.8, $p < .001$, η_p^2 = .40], indicating that participant's correct responses were slower in the first block than in the second block (1A: 4176 vs 3828 ms; 1B: 4156 vs 3879 ms). No other effects nor interactions were statistically significant ($ps > .05$).

3.1.2. Electrophysiological results
Table 1 summarizes the main electrophysiological results.
1. Encoding phase (only Experiment 1A).
P250. Time window from 200 to 300 ms after the initial sample stimulus onset.

The main effect of Outcomes was significant [F (1,56) = 19.6, $p < .001$, η_p^2 = .41] (see Figs. 3 and 4). The P250 component was larger in the DOP condition (*Mean* = 3.9 μV, *SD* = ±.45) than in the NOP condition (*Mean* = 1μV, *SD* = ±.45). There was also significant Outcomes x Caudality interaction [F (1,56) = 5.7, p = .02, η_p^2 = .17]; the wave amplitude was significantly higher in CP regions (4.3μV) than in FC regions (3.5μV) in the DOP condition [t(29) = 3.8, p = .002]. In contrast, the amplitude of the waves was similar in both ROIs in the NOP condition ($p > 0.05$). No other effects nor interactions were statistically significant ($ps > .05$).

A significant correlation between behavioral performance (accuracy) and CP signals was found just with the DOP (r_{1A} = 0.54, p = 0.038; see Fig. 5). In contrast, the correlation between accuracy and FC signals was not significant with the NOP ($p > .05$). When the two correlations (with the DOP and with the NOP) were compared using Fisher's Z transformation data, the difference was statistically significant [Z = 1.62, p = .04].

2. Maintenance phase.
P300 (i). Time window from 0 to 200 ms after the delay onset.
The ANOVA revealed significant main effects of Experiment [F (1,56) = 25,4, $p < .001$, η_p^2 = .37], Outcomes [F(1,56) = 11.7, p = .01, η_p^2 =.21]
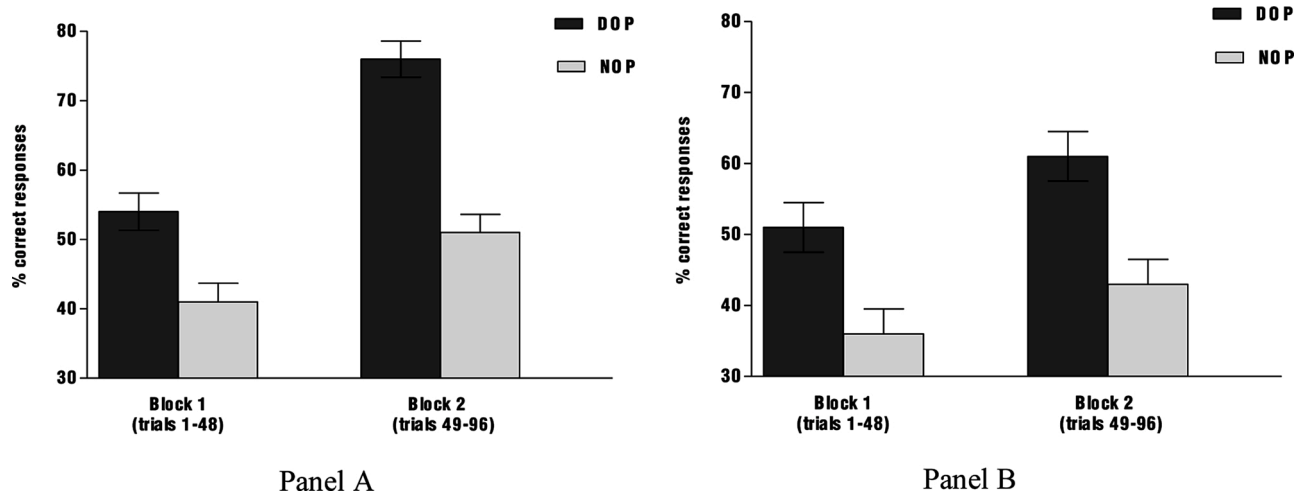
Fig. 2. Mean percentage of correct responses as a function of Outcomes (DOP vs NOP) and Block, in Experiments 1A (panel A) and 1B (panel B). Error bars represent the standard deviations.

Table 1
Results from ANOVAs (mean voltage data) in ERP component's time window grouped by Experiment (1A, 1B), Outcomes condition (DOP, NOP), Caudality (FC, CP), and Laterality (left, middle, right). ANOVAs on ERPs amplitudes. PSW (positive-slow wave). NSW (negative-slow wave). CNV (contingent negative variation).

Phase	Time window	ERP Component	ANOVAs				
			Experiment	Outcomes	Caudality	Laterality	Significant Interactions
Encoding	200–300 after sample onset	P250	–	*	n.s.	n.s.	Outcomes x Caudality
	0–200	P300 (i)	*	*	*	n.s.	Outcomes x Caudality
	200–1000	Early PSW	*	*	n.s.	n.s.	Experiment x Outcomes x Caudality
Maintenance 0 start from delay period onset	1000–2000	Early PSW-NSW	*	*	n.s.	n.s.	n.s.
	2000–5000	Late PSW-NSW	*	*	*	n.s.	-Experiment x Outcomes x Caudality -Experiment x Outcomes x Laterality
Retrieval 0 start from comparison stimuli onset	100–200	N100	*	*	n.s.	n.s.	Outcomes x Caudality
	300–600	P300 (ii)	n.s.	*	*	n.s.	n.s.
	700–1700	CNV	n.s.	*	n.s.	n.s.	n.s.

n.s.=p>.05; *=p<.05.

and Caudality [$F(1,56) = 29, p < .001, \eta_p^2 = .40$] (see Figs. 3 and 6). The P300 (i) component showed higher amplitude in Experiment 1B (*Mean* = 5 μV, SD = ±.63) than in Experiment 1A (*Mean* = 1.8μV, SD = ±.63); in the DOP (*Mean* = 4.5μV, SD = ±.63) than in the NOP (*Mean* = 2.4μV, SD = ±.63); and in the CP signal (*Mean* = 4 μV, SD=±.20) than in the FC signal (*Mean* = 2.9 μV, SD=±.20) (see Table 1). There was also a significant Outcomes x Caudality interaction [$F(1,56) = 4.2, p = .04, \eta_p^2 = .10$]. The amplitude was significantly higher in CP (4.2μV) than in FC (2.3μV) ROIs in the DOP condition [$t(29) = 7.5, p < .001$]. In contrast, the amplitude of the waves was similar in the two ROIs in the NOP condition ($p > 0.05$).

No other effects nor interactions were statistically significant (*ps*> .05).

Significant correlations between behavioral performance (accuracy) and CP signals ($r_{1A} = 0.55, p = 0.034; r_{1B} = 0.59, p = 0.02$) were found just in the DOP. In contrast, the correlations between accuracy and both CP and FC signals were not significant with the NOP in both experiments (*ps* > .05). When the correlations with the DOP and the NOP were compared using Fisher's Z transformation data, the differences were statistically significant [$Z_{1A} = 1.76, p = .039; Z_{1B} = 1.71, p = .044$].

Early PSW. Time window from 200 to 1000 ms after the delay onset.

The ANOVA revealed significant main effects of Experiment [$F(1,56) = 31.3, p < .001, \eta_p^2 = .36$] and Outcomes [$F(1,56) = 39.8, p < .001, \eta_p^2$

= .42] (see Figs. 4 and 6). The early PSW had a higher amplitude in Experiment 1B (*Mean* = 3.6μV, SD = ±.26) than in Experiment 1A (*Mean* = 1.6μV, SD = ±.26), and in the DOP (*Mean* = 3.8μV, SD = ±.36) than in the NOP (*Mean* = 1.5μV, SD = ±.36). There was also a significant Experiment x Outcomes x Caudality interaction [$F(1,56) = 4, p = .05, \eta_p^2 = .07$]. In Experiment 1A, there was a significant effect of Outcomes [$F(1,28) = 17.7, p < .001, \eta_p^2 = .39$], and a significant interaction Outcomes x Caudality [$F(1,28) = 10.5, p = .003, \eta_p^2 = .24$]. Further analysis showed that only in the FC region there was a main effect of Outcomes [$F(1,28) = 21.5, p < .001, \eta_p^2 = .43$] in this experiment; the early PSW had a higher amplitude in the DOP (*Mean* = 2.2μV, SD = ±.28) than in the NOP (*Mean* = .32μV, SD = ±.28). In Experiment 1B, Outcomes produced a significant main effect ([$F(1,28) = 24.7, p < .001, \eta_p^2 = .47$]; in the early PSW component the DOP showed higher amplitude than the NOP in both the FC region (DOP: *Mean* = 5.6μV, SD = ±.53; NOP: *Mean* = 2.3μV, SD = ±.53) and the CP region (DOP: *Mean* = 4.9μV, SD = ±.45; NOP: *Mean* = 1.7μV, SD = ±.45).

No other effect, nor interactions were statistically significant (*ps*> .05).

Early PSW-NSW. Time window from 1000 to 2000 ms after the delay onset.

The ANOVA revealed significant main effects of Experiment [$F(1,56) = 19.8, p < .001, \eta_p^2 = .26$] and Outcomes [$F(1,56) = 42.5, p < .001, \eta_p^2$
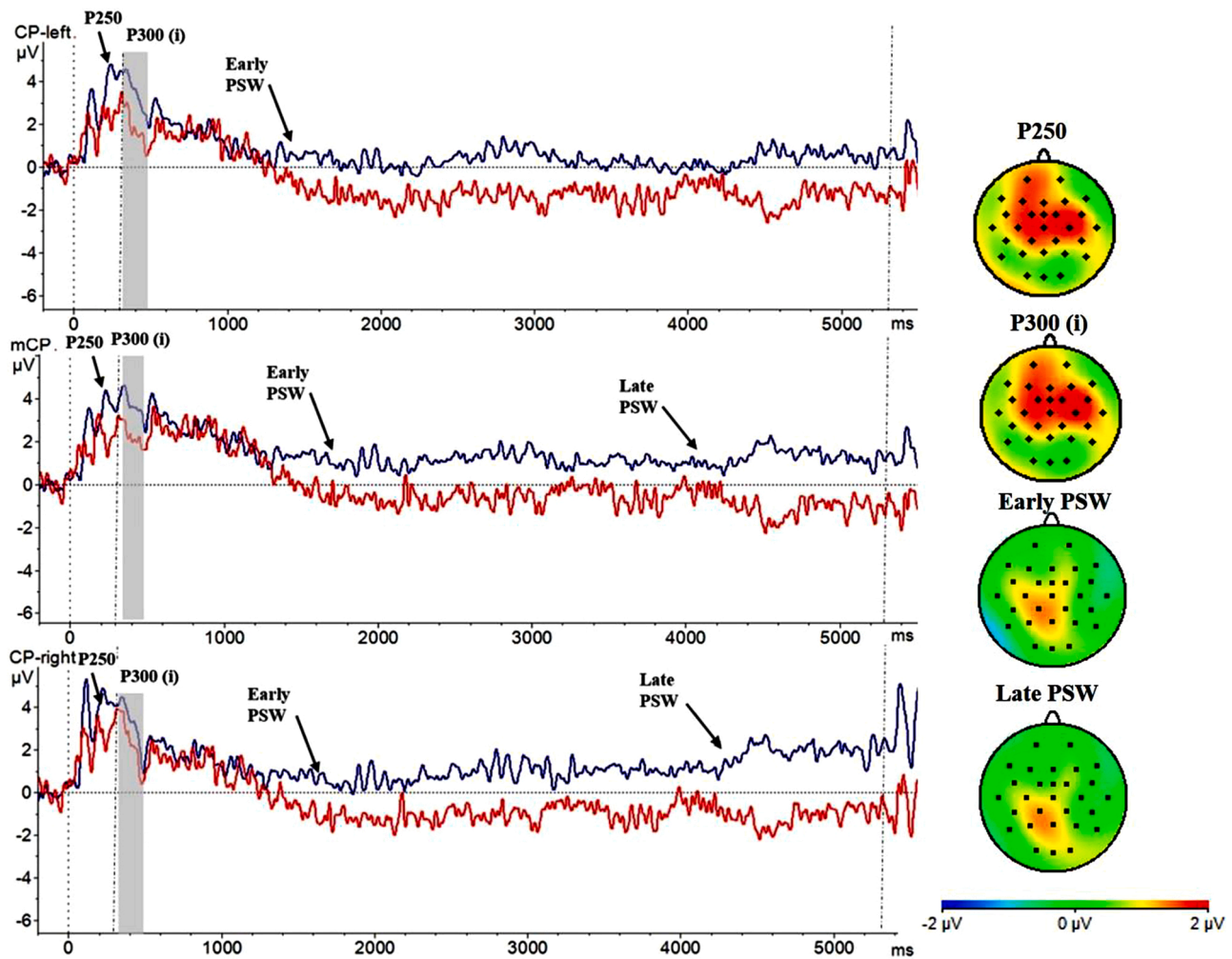
Fig. 3. Grand-average voltage data (in μV) of centro-parietal-left (CP-left), medial centro-parietal (mCP) and centro-parietal-right (CP-right) signals in Experiment 1A, as a function of Outcomes (DOP, blue line vs. NOP, red line). Grey rectangular shades represent P300 (i) time windows in the maintenance phase. Time zero represents initial sample stimulus onset. Delay period between vertical dotted lines from 300 to 5300 ms. PSW, Positive-Slow Wave. Topographic maps (right) of the differences in the ERP waves between the DOP and the NOP in each time window.
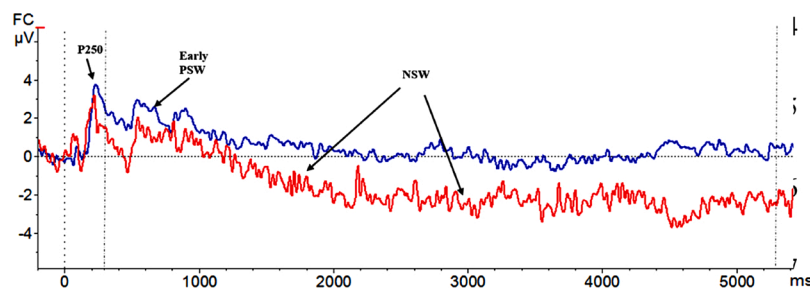

Fig. 4. Grand-average voltage data (in μV) of fronto-central waves in Experiment 1A, as a function of Outcomes (DOP, blue line vs. NOP, red line). Time zero represents initial sample stimulus onset. Delay period between vertical dotted lines from 300 to 5300 ms. PSW, Positive-Slow Wave. NSW, Negative-Slow Wave.

= .43] (see Figs. 4 and 6). The PSW component had a higher amplitude in Experiment 1B (*Mean* = 1.5μV, *SD*=±.27) than in Experiment 1A (*Mean* =−.2μV, *SD* = ±.27), and in the DOP (*Mean* = 2μV, *SD*=±.27) than in the NOP (*Mean* = −.6μV, *SD* = ±.27).

No other effects nor interactions were statistically significant (*ps*> .05).

Late PSW-NSW. Time window from 2000 to 5000 ms after the delay onset.

The analysis indicated significant main effects of Experiment [F (1,56) = 18.5, $p < .001$, $\eta_p^2 = .25$], Outcomes [F (1,56) = 56.3, $p < .001$,

$\eta_p^2 = .50$], and Caudality [F (1,56) = 31.6, $p < .001$, $\eta_p^2 = .36$]; the signal mean was higher in Experiment 1B (*Mean* = .92μV, *SD*=±.21) than in Experiment 1A (*Mean* =−.33μV, *SD* = ±.21); the PSW component was observed in the DOP (*Mean* = 1.3μV, *SD*=±.21) whereas the NSW component was observed in the NOP (*Mean*= −.8μV, *SD* = ±.21); and the CP signal (*Mean* = .8 μV, SD = ±.17) was greater than the FC signal (*Mean* = −.2 μV, SD = ±.17). The above main effects were modulated by a significant three-way interaction between these factors [F (1,56) = 10.3, $p = .002$, $\eta_p^2 = .16$]. The analysis of the interaction revealed important findings. Firstly, there was a significant interaction
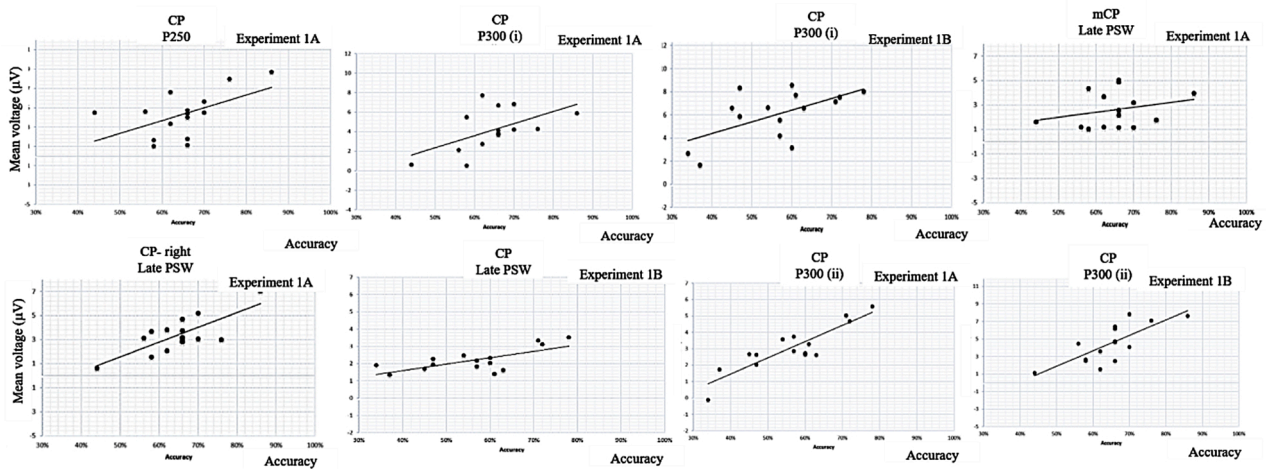
Fig. 5. Correlation between mean voltage (in µV) in the centro-parietal region (CP) and accuracy in P250, P300 (i), Late PSW, and P300 (ii) time windows in the DOP. Experiment 1A and 1B. PSW, Positive-Slow Wave.
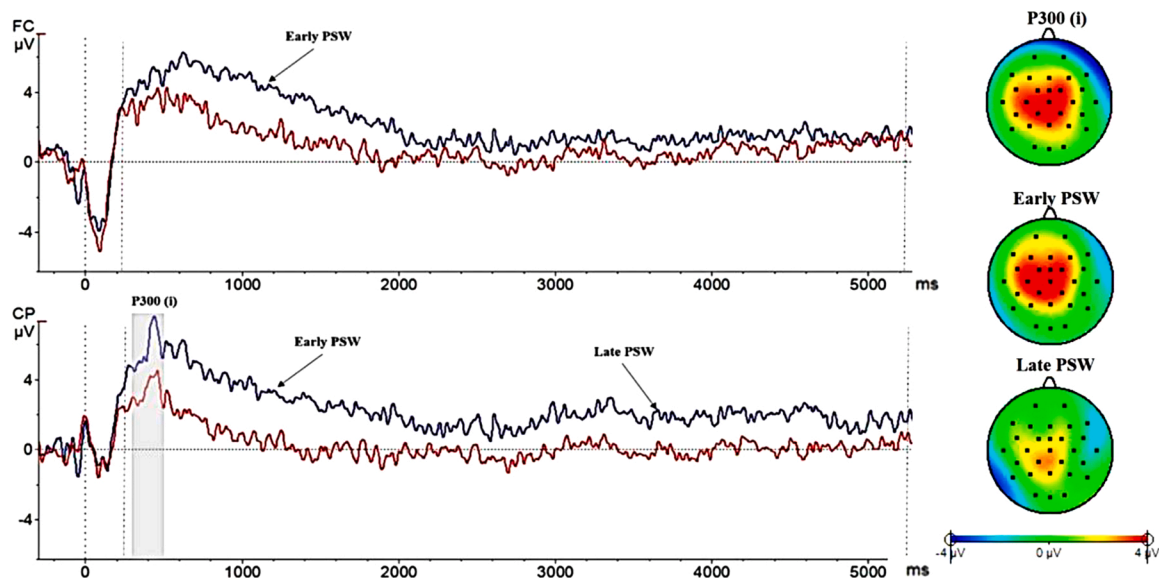

Fig. 6. Grand-average voltage data (in µV) of fronto-central (FC) and centro-parietal (CP) signals in Experiment 1B, as a function of Outcomes (DOP, blue line vs. NOP, red line). Grey rectangular shades represent P300 time windows in the maintenance phase. Time zero represents initial stimulus onset. Delay period between vertical dotted lines from 300 to 5300 ms. PSW, Positive-Slow Wave. Topographic maps (right) of the differences in the ERP waves between the DOP and the NOP in each time window.

Experiment x Outcomes [$F(1,56) = 4.1, p = .04, \eta_p^2 = .12$] in FC region. The difference between the DOP and the NOP in FC regions was significant just in Experiment 1A [$F(1,28) = 67.3, p < .001, \eta_p^2 = .71$] (see Fig. 4). More specifically, the NSW component was registered in the NOP (*Mean* = −2.6µV, SD = ±.23) but not in the DOP (*Mean* = .04µV, SD = ±.23) in this experiment. Secondly, the effect of Outcomes was significant in both experiments in CP region [$F(1,56) = 67, p < .001, \eta_p^2 = .55$]. That is, the PSW component was found in the DOP (*Mean* = 2 µV, *SD* = ±.21) but not in the NOP (*Mean* = −.43µV, *SD* = ±.21).

The Experiment x Outcomes x Laterality interaction was also significant [$F(2,55) = 3.8, p = .03, \eta_p^2 = .12$]. Further analyses showed that there was a significant Outcomes x Laterality interaction just in Experiment 1A [$F(1,28) = 15.7, p < .001, \eta_p^2 = .36$] due to the Laterality effect was found just in the DOP [$F_{1A}(1,14) = 25.8, p < .001, \eta_p^2 = .65$]. As it can be observed in Fig. 3, a significant higher amplitude was registered over the right hemisphere (3 µV) compared to the: i) left hemisphere (.52 µV) [$t_{1A}(14) = 5.9, p < .001$]; and ii) midline (1.6 µV), [$t_{1A}(14) = 4.9, p < .001$]. The left hemisphere was significantly less positive than the

midline [$t_{1A}(14) = 2.4, p = .03$]. There were no significant differences between the activity registered in the three regions in the NOP ($ps > .05$).

Correlations between behavioral performance (accuracy) and CP signals were found in both experiments, but only in the DOP (CP-right: $r_{1A} = 0.8, p < 0.001$; mCP: $r_{1A} = 0.53, p = 0.045$; CP: $r_{1B} = 0.7, p = 0.003$) (see Fig. 5). Correlations were not significant in neither ROI in the NOP ($ps > 0.05$). When the correlations with the DOP and the NOP were compared using Fisher's Z transformation data, the differences were statistically significant [CP-right: $Z_{1A} = 2.14, p = .01$; mCP: $Z_{1A} = 1.74, p = .04$; CP: $Z_{1B} = 2.17, p = .02$].

Table 2 summarizes the estimated Bayes factors (BF$_{10}$) obtained when comparing ERPs signals in the slow long-latency waves time window under study and baseline in each Outcomes condition, in both experiments. The Bayesian analyses were performed using SPSS version 25.0 (IBM Corp., 2017).

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

N100. Time window from 100 to 200 ms after the comparison stimuli

Table 2

Bayes factor obtained by comparing the electrical activity in each subinterval (200 ms) with the baseline as a function of ROI (FC and CP), Outcomes (DOP and NOP) and Experiment (1A and 1B). A 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 & Wagenmakers, 2013).

| Late PSW-NSW time window | 1A. Bayes factor | | | | 1B. Bayes factor | | | |
| | FC region | | CP region | | FC region | | CP region | |
	DOP	NOP	DOP	NOP	DOP	NOP	DOP	NOP
2000	,103*	5*	500***	, 610	,085**	20**	10**	,115*
2200	,123*	250***	333***	,425	,124*	10**	10**	,117*
2400	,106*	500***	250***	,165*	,182*	20**	250***	,122*
2600	,096*	333***	500***	,118*	,158*	1000***	500***	,138*
2800	,228*	1000***	500***	,198*	,121**	1000***	1000***	,078**
3000	,009***	500***	250***	,116*	,136*	500***	500***	,086**
3200	,003***	500***	500***	,183*	,712	500***	500***	,073**
3400	,006***	500***	1000***	,080**	,084**	>1000***	333***	,095**
3600	,008***	1000***	333***	,095**	,097**	>1000***	1000***	,091**
3800	,002***	500***	>1000***	,074**	,064**	1000***	1000***	,081**
4000	,098**	500***	>1000***	,186*	,063**	1000***	250***	,063**
4200	,064**	1000***	500***	,163*	,083**	500***	500***	,071**
4400	,066**	>1000***	500***	,726	,124*	1000***	>1000***	,126*
4600	,162*	>1000***	>1000***	,613	,135*	>1000***	1000***	,131*
4800	,174*	500***	500***	,822	,187*	1000***	500***	,168*
Accepted Hyp.	H0	H1	H1	H0	H0	H1	H1	H0

onset.

The ANOVA showed significant main effects of Experiment [F (1,56) = 18.1, p = .001, η_p^2 = .25] and Outcomes [F (1,56) = 11.2, p = .03, η_p^2 = .19] (see Figs. 7 and 8). The amplitude was lower in Experiment 1A (*Mean*= −.1 μV, *SD*=±.22) than in Experiment 1B (*Mean* = −1.5μV, *SD*=±.22). The N100 was observed in both outcomes conditions, with lower amplitude in the DOP (*Mean*= −.1μV, *SD*=±.25) than in the NOP (*Mean* = −.91μV, *SD*=±.26). There was a significant Outcomes x Caudality interaction [F (1,56) = 15.1, p = .01, η_p^2 = .23]. Analyses of the interaction revealed that there was a significant effect of Outcomes just in the CP region [F (1,56) = 23, p = .003, η_p^2 = .31], with lower amplitude in the DOP (*Mean*= −0.2μV, *SD*=±.28) than in the NOP (*Mean* = −1μV, *SD*=±.28).

No other effects nor interactions were statistically significant (*ps*> .05).

P300 (ii). Time window from 300 to 600 ms after the comparison stimuli onset.

The analysis showed significant main effects of Outcomes [F (1,56) = 35.1, p < .001, η_p^2 = .39] and Caudality [F (1,56) = 16.8, p < .001, η_p^2 = .23] (see Figs. 7 and 8). The P300 (ii) component had a higher amplitude in the DOP (*Mean* = 3.3μV, *SD*=±.35) than in the NOP (*Mean* = .4μV, *SD*=±.35) and in the CP region (*Mean* = 2.3μV, *SD*=±.23) than in the FC region (*Mean* = 1.4μV, *SD*=±.23).

No other effects nor interactions were statistically significant (*ps*> .05).

Correlations between behavioral performance (accuracy) and CP ERPs were found in both experiments (r_{1A} = 0.7, p = 0.01; r_{1B} = 0.5, p = 0.004) but only in the DOP (see Fig. 5). There were not significant correlations in the NOP in neither ROI (*ps*>0.05). When the correlations with the DOP and the NOP were compared using Fisher's Z transformation data, the differences were statistically significant [Z_{1A} = 1.8, p = .03; Z_{1B} = 1.7, p = .04].

CNV. Time window from 700 to 1700 ms after the comparison stimuli onset.

The ANOVA revealed a significant main effect of Outcomes [F (1,56) = 27.2, p < .001, η_p^2 = .41] (see Figs. 7 and 8). The CNV was larger in the
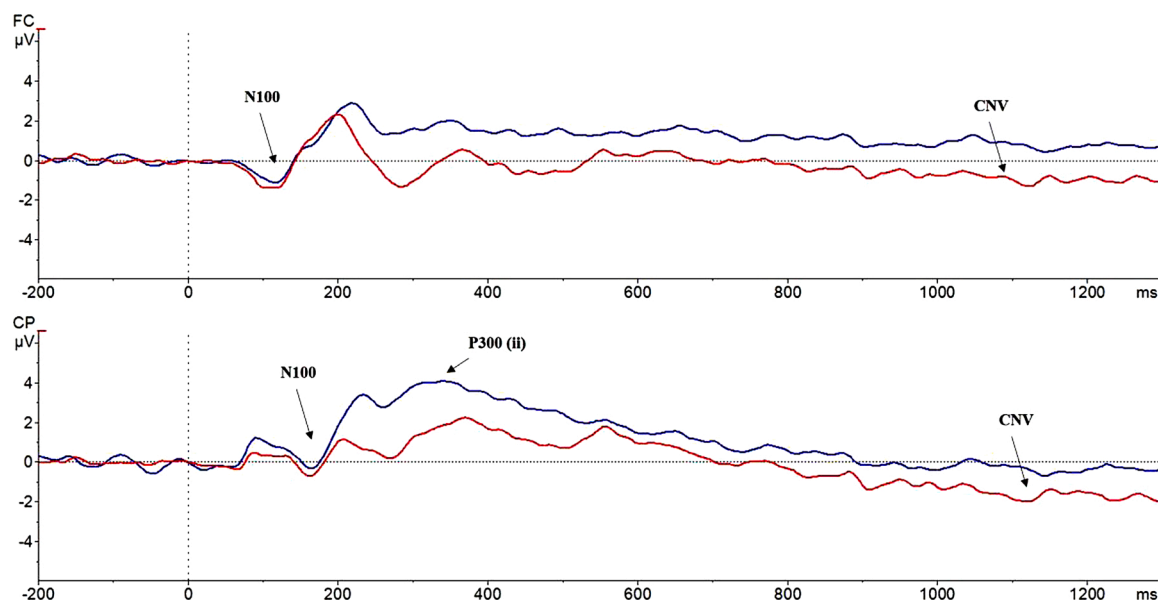
Fig. 7. Grand-average voltage data (in μV) of fronto-central (FC) and centro-parietal (CP) signals in Experiment 1A, as a function of Outcomes (DOP, blue line vs. NOP, red line) in the retrieval phase. Time zero represents comparison stimuli onset. CNV, Contingent Negative Variation.

Fig. 8. Grand-average voltage data (in μV) of fronto-central (FC) and centro-parietal (CP) signals in Experiment 1B, as a function of Outcomes (DOP, blue line vs. NOP, red line) in the retrieval phase. Time zero represents comparison stimuli onset. CNV, Contingent Negative Variation.
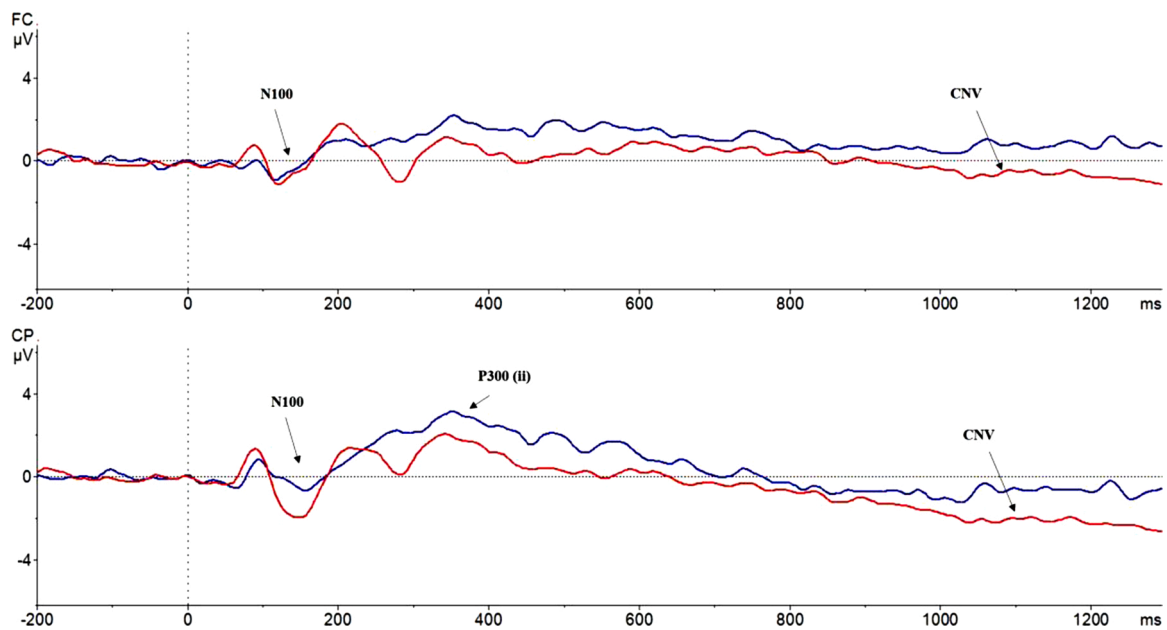
NOP (*Mean*=−1.8μV, *SD*=±.42) than in the DOP (*Mean* = .32μV, *SD*=±.42). No other effects nor interactions were statistically significant (*ps*> .05).

4. Discussion

In this study, we explored the temporal dynamics of short-term memory processes in both the DOP and the NOP in the absence of awareness of either the outcome (Experiment 1A) or the initial sample stimulus (Experiment 1B). To this end, ERPs were recorded during the performance of a recognition memory task.

The behavioral results from both experiments were similar to those found in a previous study (Carmona et al., 2019). That is, (i) performance in Experiment 1B was worse than that in Experiment 1A due to increased task difficulty by presenting masked sample stimuli and (ii) visual recognition memory was improved when participants were trained with the DOP, relative to the NOP, in both Experiments 1A (subliminal outcome) and 1B (subliminal initial sample stimulus). This finding is in agreement with the two-memory systems theory (e.g., Savage & Ramos, 2009) by demonstrating that being aware of the specific outcomes of our choices is not a necessary condition to enable the beneficial effect on cognition observed when the DOP is applied. As the model claims, the expectancies of the specific outcomes appear to be implicitly formed after several initial sample stimulus-specific outcome pairings, through classical conditioning associations. Thus, when the initial sample stimulus is displayed, an internal representation of its unique outcome (the outcome expectancy) would be activated in an automatic and non-intentional way, triggered by implicit-prospective processes, and would stay active during the delay period. Our results show that the explicit knowledge of the outcomes or the initial sample stimuli is not needed to form, activate, and maintain these expectancies indicating that the beneficial effects of the DOP depend on implicit mechanisms (see Carmona et al., 2019).

According to our initial hypothesis, the electrophysiological results from both experiments revealed differences in all the three phases of the short-term memory process: encoding, maintenance, and retrieval as a function of the outcomes condition (DOP vs. NOP). Regarding the encoding phase, several previous studies suggest that stimuli-reward associations enable the encoding of visual information (Gong & Li, 2014; Infanti, Hickey, & Turatto, 2015), and that these associations

influence working memory even at a very early stage of the memory process (Infanti et al., 2015; Infanti, Hickey, Menghi, & Turatto, 2017). Our results support this hypothesis. In fact, in the encoding phase of the Experiment 1A, the results showed differences between the DOP and NOP in the amplitude of the P250 component, an early P300 that was extended several milliseconds after the initial sample stimulus offset (the P300 (i) observed in the delay period). These positive waves observed in the CP region are related to reward expectancies in the evaluation and categorization of the initial sample stimuli (e.g., Holroyd et al., 2011; Novak & Foti, 2015). Our data revealed the P250 only in the DOP, whereas a negative deflection was rather found in the NOP in the same time window. Considering that reward stimuli usually elicit more positive amplitudes (Hughes et al., 2013), our results support the two-memory system model proposed by Savage and colleagues (v.g., Savage & Ramos, 2009) indicating that only the training with the DOP allowed to establish expectancies of the unique outcome associated with the initial sample stimulus and that these expectancies affected the encoding phase. Furthermore, the P250 component has been also described as an early biomarker of short-term storage (Chapman et al., 2015). Our results suggest that P250 amplitude could be enhanced by specific outcomes. Finally, the lower amplitude of P250 in the FC region observed in the NOP could be explained by a neural suppression in frontal areas due to visual repetition priming that results in a reduced positivity often observed from 100 ms to 500 ms after the initial sample stimulus onset (Eddy, Schmid, & Holcomb, 2006; Race, Shanker, & Wagner, 2009; Schacter, Wig, & Stevens, 2007).

Importantly, in Experiment 1A, during the maintenance phase, a larger NSW was registered in the FC region in the NOP, supporting the idea that a mental representation of the initial sample stimulus would keep active over the delay to correctly solve the task (Kuo et al., 2012; Mecklinger & Pfeifer, 1996; Ruchkin et al., 1990, 1992). In contrast, a more positive PSW component was observed during the same period (the four last seconds of the delay) in the CP region in the DOP. This PSW component is usually elicited during outcome processing following the feedback display (Novak & Foti, 2015; Pornpattananangkul & Nusslock, 2015; Ruchkin et al., 1995). Once more, the present results are in agreement with the two-memory systems theory (e.g., Savage & Ramos, 2009), which proposes that when differential outcomes are arranged, an internal and automatic representation of the unique outcome associated with a specific initial sample stimulus would remain active, through a

prospective process, during the delay period. In addition, it must be noted that this positive slow wave was significantly larger in the right hemisphere than in the left hemisphere over the last three seconds of delay. This laterality effect has been found in several studies with masked stimuli, suggesting a posterior positivity larger over the right hemisphere (Dehaene & Changeux, 2011; Dehaene et al., 2001; Eddy et al., 2006).

It is worth noting that in Experiment 1B, contrary to our initial hypothesis, the NSW was not found in the FC region in the NOP in the maintenance phase. This negative wave, as above mentioned, is usually enabled from an internal representation of the initial sample stimulus which has just been seen. Given that the initial sample stimulus was subliminally presented in Experiment 1B, it seems that its retention was not possible. This observation is incompatible with our previous suggestion that retrospective memory can be activated spontaneously, being a subliminal encoding of the stimulus sufficient to engage it (Carmona et al., 2019; see also Mok, 2012). We think that visual repetition priming might be the main contributor to the recognition of the stimuli observed in the NOP (Ko, Duda, Hussey, Mason, & Ally, 2014; Zhang, Begleiter, Porjesz, & Litke, 1997). In line with that contention, a reduction in neural activity, less positivity, in frontal regions was found from 100 ms to 500 ms after the masked sample stimulus onset and following the comparison stimuli onset (Race et al., 2009; Schacter et al., 2007; see Figs. 4 and 6). On the other hand, the PSW was found in the delay period without a laterality effect, probably due to the fact that the outcomes in this task were supraliminally presented.

During the retrieval phase, following the comparison stimuli onset, the EEG data from both experiments revealed differences in the amplitude of the N100 component between both outcomes conditions, with a higher amplitude in the NOP than in the DOP in CP-regions (Downing, 2000; Olivers, 2007; Zanto & Gazzaley, 2009). This component has been associated with control mechanisms responsible for reducing the interference from distracting stimuli, a top-down control process (or endogenous attention) that is modulated by expectancies (Kuo et al., 2012; Zanto & Gazzaley, 2009). In fact, a lower amplitude is observed in N100 when the expectancies are high (Kuo et al., 2012; Zanto & Gazzaley, 2009). The idea that the rewarded stimuli capture attention involuntary requiring less controlled attentional resources to correctly solve a task has been suggested by recent research (Anderson, Laurent, & Yantis, 2011a, b; Anderson, Laurent, & Yantis, 2014; Infanti et al., 2015). Accordingly with the hypothesis that in the NOP more attentional resources seem to be necessary to successfully complete the task, we found that the CNV elicited in both regions, CP and FC, was observed only in that condition. This negative wave in FC regions is associated with the enablement of attentional and perceptual anticipatory processes (Glazer et al., 2018; Gómez, Flores, & Ledesma, 2007). In addition, the P300 (ii) component was also registered in both outcomes conditions in CP and FC regions, with a greater amplitude in the DOP than in the NOP. Previous research has suggested that higher amplitude in the P300 (ii) in CP regions might reflect a less difficulty to discriminate among stimuli in the former condition (Näätänen & Picton, 1987).

Finally, a greater positive slow wave amplitude in Experiment 1B compared to Experiment 1A was systematically observed in all the time windows under study. We think that this might be due to the higher number of times the sample stimulus was presented in Experiment 1B (twice as many as in Experiment 1A), which could have led to a training effect usually reflected in an increase in the amplitude of positive waves (Gajewski & Falkenstein, 2018).

Regarding the relationship between the ERP signals and task accuracy, it is important to highlight that in neither of the two experiments (1A and 1B) there was a significant correlation between participants' performance and the ERP components registered in the NOP: negative deflection in P250 time window (only registered in Experiment 1A), P300 (i), NSW, N100, P300 (ii), and CNV. Thus, the activation of those components could reflect effort, but no efficacy in the task. In clear contrast, the correlation analyses between accuracy and the EEG data

with the DOP showed that better performance was associated with a centro-parietal EEG positivity in P250, P300 (i), late PSW and P300 (ii) in both experiments. These findings extend the results of the study by Carmona et al. (2020) and provide evidence for a greater efficiency across most of the components analyzed with the DOP.

In sum, the neuronal electrical patterns explored in this study revealed that different mechanisms were activated depending on the outcomes condition, which is consistent with previous studies (Carmona et al., 2019; Carmona et al., 2020; Mok, 2012; Mok, Thomas, Lungu, & Overmier, 2009) as well as with the two memory system model proposed by Savage and colleagues (e.g., Savage & Ramos, 2009). To our knowledge, the present findings provide, for the first time, electrophysiological evidence of implicit prospective processes involved in the DOP, which result in an improved visual recognition memory. In addition, the effects on the N100 and P300 components in the retrieval phase suggest that the DOP also influences attentional processes. Future studies should further explore this issue by testing, for instant, how attentional and memory processes might interact to enhance performance in learning and memory tasks.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgements

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.biopsycho.2020.107987.

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