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Event-related potentials elicited by unexpected visual stimuli after voluntary actions

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Abstract

Event-related potentials from visual stimuli that were presented after voluntary actions were recorded to examine how people expect their action effects. Participants pressed a button in response to a cue stimulus (*L* or *R*) either in the fixed condition where participants always pressed a center button or in the choice condition where they selectively pressed the corresponding left or right button. Immediately after the button press, a second stimulus (*left* or *right*) was presented visually to inform that their action was registered. When the second stimulus did not match the cue stimulus ($p = .20$), a late positive potential (LPP) with a posterior scalp distribution occurred in a latency range of 500–700 ms. The amplitude of this mismatch-related LPP was larger in the choice condition than in the fixed condition. The results suggest that the cognitive mismatch between the expected and actual action effects is reflected in the LPP, and the selection of a specific action strengthens the expectation of its action effect.

Key words

Event-related potentials, Cognitive mismatch, Action effect, Action selection, P300, Positive slow wave

1. Introduction

Goal-directed voluntary action has been thought to be initiated by anticipating its effect. This idea, called the ideomotor theory, has a long history and is still receiving heightened interest in cognitive psychology (Stock and Stock, 2004). To understand how people initiate an action and how they expect the effect of their action is a fundamental question not only in basic research including neuroscience (Blakemore et al., 1998; Elsner et al., 2002) but also in applied settings. For instance, when people interact with a tool (e.g., personal computer, household appliance), users execute an action with an expectation of the desirable state (Norman, 1986). To facilitate the interaction, the machine often provides a signal or “feedback” which informs that the user’s operation is registered. However, it is not clear how this information is processed by the user.

Event-related brain potentials (ERPs) have been proposed to be a tool of assessing the state of attention in human-computer interaction (Nittono, 2005; Nittono et al., 2003). Previous studies have shown that the frontocentral P3 (P3a) elicited by rare deviant stimuli is enhanced when a participant controls the initiation of stimulus presentation by pressing a single trigger button, compared to when a computer controls the stimulus initiation without a participant’s action (Nittono, 2004; Nittono and Ullsperger, 2000). This result is interpreted as indicating that action or action planning activates perceptual representation of the most probable action effect and the deviance from the expectation is reflected as the P3a enhancement (Nittono, 2006).

Although the effect of self-stimulation on ERPs has been documented using a task containing a single type of action, little is known about whether participants can selectively anticipate their action effects when they have more than one action options. In the present study, we asked participants to press a button in response to a cue stimulus (*L* or *R*) at their pace. Immediately after the button press, one of the two visual stimuli (*left* or *right*) was presented to inform that their action was registered. The type of the second stimulus could be predicted by the type of the cue stimulus. They were matched in most trials (p = .80), but sometimes mismatched (p = .20). We assumed that, if participants expected a specific stimulus after button press and the actual action effect did not match their expectation, the cognitive mismatch would be reflected in ERPs.[1] Specifically, we assumed that a late positive potential (LPP) would be elicited by infrequent mismatched stimuli. This prediction was based on a recent study using a flanker task (Ehlis et al., 2005), in which participants were asked to press either the left or right button (corresponding to "H" or "S") in response to a visual stimulus (e.g., HHSHH, SHSHS). Immediately after the button press, the chosen letter (H or S) was presented visually as a "response feedback." A late positive wave with a central scalp distribution was elicited around 500–800 ms when the incorrect stimulus (i.e., the letter that did not match the button pressed) was given as the response feedback (4 % of the total trials). We assume that this positivity may be similar to the P300 (P3b), which is elicited by unexpected rare events (Donchin and Coles, 1988), but in this paper we will use an observational term LPP for descriptive purpose.

In the present study, we examined the effect of action selection on this mismatch-related LPP by comparing two conditions: (1) the condition in which participants had two buttons to choose (choice condition), and (2) the condition in which they had a fixed single button (fixed condition). In both conditions, the probabilities of the cue and second stimulus pairs (match: L–left, R–right [p = .40 each], mismatch: L–right, R–left [p = .10 each]) were the same. From the information theory perspective, a cue stimulus predicts the second stimulus with the same certainty either with or without a selective response. Therefore, it is possible to hypothesize that the response selection has no effect on ERPs at all. On the other hand, it is also possible to hypothesize that response selection enhances the expectation of a specific action effect because the selected action itself may serve as a memory aid to maintain the cue stimulus information. If this is the case, the mismatch between the expected and actual action effects becomes clearer, and a larger LPP would be elicited in the choice condition.

In addition, we examined whether the task relevance of action effects modulates the effect of action selection on ERPs. At the beginning of the experiment, participants performed both the fixed and choice conditions without instructions about the occasional mismatch between a cue and the second stimulus. Then, they were asked to perform both conditions again while counting the mismatches silently. Because participants attended actively to action effects in the latter condition, a larger P300 or LPP would be elicited. On the other hand, the effect of action selection would be expected to be similar, if it served as a memory aid for comparing a cue stimulus and the second stimulus.

2. Method

2.1. Participants

Twelve student volunteers participated in the study (6 men and 6 women, 20-27 years old, mean age 22.8 years). All of them had normal or corrected-to-normal vision and were right-handed according to a questionnaire (Oldfield, 1971). None had a history of psychiatric/neurological disorders or drug/alcohol abuse. They gave written informed consent as per the Helsinki declaration.

2.2. Procedure and stimuli

Figure 1 shows a schematic diagram of the task used in the experiment. In all conditions, each trial consisted of three steps: (1) an alphabetic letter, either *L* or *R* (p = .50 each), was displayed for 200 ms as a cue stimulus, (2) participants pressed a designated button in each condition at their pace, and (3) within 10 ms after the button press a word *left* or *right* was displayed as a second stimulus for 100 ms to inform that the button press was registered. A three-button response box without verbal labels was used. No speeded response was required. Participants were asked to keep their eyes on the screen and see the cue and second stimuli. They were matched in most trials (i.e., *L* predicted *left* and *R* predicted *right*, p = .80), but sometimes they were mismatched (p = .20). Because the two types of cue stimuli (*L* or *R*) were presented with equal probability, the two types of second stimuli (*left* or *right*) were also presented equally (p = .50 each), when collapsing across match trials (e.g., *left* followed *L*, p = .40) and mismatch trials (e.g., *left* followed *R*, p = .10). Cue and second stimuli were presented on a CRT monitor (refresh rate 100 Hz) with visual angles of 1° × 1° and 0.8° × 2°, respectively. The letters were presented in white against a black background. Inter-trial intervals varied between 1,300 and 1,800 ms (mean 1,500 ms).

They were four conditions. In the first two conditions, participants were simply told that each button press was followed by a visual stimulus, without being informed about the occurrence of mismatch (*no instruction* conditions). In the *fixed* condition, participants were asked to press a center button with the middle finger regardless of the type of cue stimulus. In the *choice* condition, participants had to select and press the corresponding left or right button according to the cue stimulus with either the index or ring finger. The order of conditions and response hands were counterbalanced across participants. Each condition consisted of two blocks containing 110 trials each. To foster participants' expectation that the second stimulus would match the cue stimulus, the first 10 trials in each block contained no mismatched stimuli. In trials 11−110, 80 matched and 20 mismatched stimuli occurred randomly. After these no instruction conditions, participants were told explicitly about the mismatches and asked to count them silently and to report the number after each block (*count* conditions). No feedback was given about the correctness. Under this count instruction, participants performed the fixed and choice tasks in the same order as in the no instruction conditions. Hereafter, we will call these conditions as *fixed+count* and *choice+count* conditions. To avoid the carry-over effect of count instruction, we always run the no instruction condition first.

2.3. Electrophysiological recording

An electroencephalogram (EEG) was recorded from 31 scalp electrode sites (Fp1, Fpz, Fp2, F7, F3, Fz, F4, F8, FT7, FC3, FCz, FC4, FT8, T7, C3, Cz, C4, T8, TP7, CP3, CPz, CP4, TP8, P7, P3, Pz, P4, P8, O1, Oz, and O2) according to the extended 10-20 system using sintered Ag/AgCl electrodes. Electrode impedances were kept below 10 kΩ. The data were re-referenced to mathematically linked mastoids offline. Vertical and horizontal electrooculograms (EOGs) were also recorded. These signals were recorded with a filter bandpass of 0.016 Hz (time constant 10 s) to 100 Hz and digitized at 500 Hz. Then, a digital bandpass filter of 0.05 Hz to 30 Hz was applied and ocular artifacts were corrected by Gratton et al.'s (1983) method implemented in Brain Vision Analyzer 1.05 (Munich, Germany). The period between 200 ms before and 1000 ms after the onset of the second stimulus was averaged separately by trial type (match vs. mismatch), condition, and site. The baseline was aligned to the mean amplitude of the 200 ms prestimulus period. The first 10 trials of each block, the trials in which participants pressed an incorrect button, and the trials in which EEG or EOG exceeded ±100 μV were excluded from the analysis. Because we were interested in endogenous ERP responses to a stimulus that did not match a participant's expectation, difference waveforms were calculated for each condition by subtracting the ERPs to matched stimuli from the ERPs to mismatched stimuli. This subtraction method is often used for assessing endogenous ERP components such as the mismatch negativity, and allows us to analyze the mismatch-related ERPs without overlapping sensory-evoked and movement-related potentials.

2.4. Statistical analysis

The LPP amplitude was measured in the difference waveforms as the mean amplitude of the period between 500 and 700 ms at 31 electrode sites. This period was selected by visual inspection of the grand mean waveforms. First, to determine whether a significant mismatch-related LPP was elicited in each condition, a 95 % confidence interval of the LPP amplitude was calculated for each condition at the most dominant site, Pz. Then, the LPP amplitude data were submitted to an analysis of variance (ANOVA) with factors of response selection (fixed vs. choice), task (no instruction vs. count), and site (5 midline sites: Fpz, Fz, Cz, Pz, and Oz). Lateral electrode sites were also analyzed by a similar ANOVA with factors of response selection, task, site (Fp1/2, F3/4, F7/8, FC3/4, FT7/8, C3/4, T7/8, CP3/4, TP7/8, P3/4, P7/8, and O1/2), and hemisphere (left vs. right). However, for the sake of brevity, we will not report the latter results here, because no significant main or interaction effects of hemisphere were found and the other results were similar in both analyses. Greenhouse-Geisser ε correction for the violation of sphericity assumption was applied when the degree of freedom was more than one. Scalp topographic differences were assessed by an ANOVA on the amplitude values scaled by vector length (McCarthy and Wood, 1985). Post hoc comparisons were made by using Bonferroni procedure. The significance level was set at .05 for all analyses.

3.1. Results

3.1. Behavioral measures

Participants almost always pressed the correct button in the choice and choice+count conditions (98.5 and 97.5 %, respectively). The means ± standard deviations of the times of responses to cue stimuli were 668 ± 242, 598 ± 235, 578 ± 222, and 638 ± 270 ms in the fixed, choice, fixed+count, and choice+count conditions, respectively. An ANOVA with factors of response selection and task showed no main effects but a significant interaction, $F(1, 11) = 8.20$, $p = .015$. However, analyses of simple main effects did not show any significant differences between conditions. In the count conditions, mismatches between the cue stimuli and the second stimuli were detected almost perfectly. The mean deviations from the correct answer (i.e., 20 in all blocks) were 0.08 and 1.08 per block in the fixed+count and choice+count conditions, respectively.

3.2. ERP

Figure 2 shows grand mean ERP waveforms. The percentages of accepted trials were similar across the conditions (82.1−93.9 %, mean 87.2 %). Compared to matched stimuli, mismatched stimuli elicited a larger positive wave in a latency range of 500−700 ms in all conditions. In the difference waveforms, 95% confidence intervals of the LPP amplitude at Pz were 1.1−4.4, 4.6−7.5, 4.8−8.2, and 5.6−10.5 μV for the fixed, choice, fixed+count, and choice+count conditions, respectively. These results indicate that a significant mismatch-related LPP was elicited in all conditions. Figure 3 shows the mean values of the LPP amplitude calculated in the difference waveforms. The LPP had a posterior scalp distribution and its amplitude was larger in the choice than in the fixed condition. The ANOVA on the LPP amplitude showed significant main effects of response selection and site, $F(1, 11)= 15.31$, $p =.002$; $F(4, 44) = 47.26$, $p < .001$, $\varepsilon = .54$, respectively. Moreover, the scalp distribution of the LPP differed between the no instruction condition and the count condition, which was shown as a significant interaction effect of task and site, $F(4, 44) = 15.55$, $p < .001$, $\varepsilon =.63$. This interaction was also significant when using the amplitude values scaled by vector length, $F(4, 44) = 4.26$, $p = .02$, $\varepsilon = .59$, which suggests that the interaction between task and site is not due to the overall amplitude differences between the conditions. Analyses of simple main effects on the raw amplitude data showed that the amplitude was significantly larger at Pz and Oz in the count condition than in the no instruction condition, although the LPP had a parietal dominant scalp distribution (Fpz < Fz < Cz < Pz, Fpz < Fz < Oz) in both conditions. Although the statistical analysis did not reveal the source of interaction clearly, Figure 3 shows that the amplitude of the LPP in the count condition appears to increase more steeply from anterior to posterior sites. The topographic maps shown in Figure 4 also corroborate this trend. The interaction between response selection and task was not significant, $F(1, 11) = 1.22$, $p = .294$. Moreover, neither the Response Selection × Site nor the Response Selection × Task × Site interaction was significant, Fs(4, 44) = 0.85 and 1.18, ps = .409 and .331, εs = .35 and .67, respectively; for scaled amplitude data, Fs(4, 44) = 2.44 and .216, ps = .11 and .86, εs = .48 and .64, respectively. These nonsignificant results suggest that response selection did not affect the scalp distribution of the LPP either in the no instruction condition or in the count condition.

4. Discussion

A posteriorly distributed positive potential (LPP) was elicited in a latency range of 500−700 ms when a visual stimulus after voluntary action (action effect) did not match the cue stimulus. Even when the stimuli were irrelevant to the task (i.e., no instruction condition), a significant LPP was elicited. Moreover, its amplitude was larger in the choice condition than in the fixed condition. When participants were required to attend to action effects (i.e., count condition), the mismatch-related LPP increased in amplitude at Pz and Oz and showed a significantly different scalp distribution compared to the LPP in the no instruction condition. However, the effect of action selection was not modulated by this count instruction.

A significant LPP was elicited by an action effect that did not match the cue stimulus even in the no instruction condition. Usually, a much smaller P300 is elicited by infrequent visual stimuli when no instruction is given (Bennington and Polich, 1999, Herbert et al., 1998). The present result suggests that people can detect the mismatch between the expected and actual effects of their action, even when these stimuli are not directly related to the task. There may exist a mechanism to process the consequence of one’s action automatically without intention. The reason for a longer-than-usual peak latency (about 550 ms) of the LPP may be because it took time to compare the second stimulus with the cue stimulus, as in a kind of memory search task (Verleger, 1997). Contrary to the previous experiments (e.g., Nittono, 2006), no frontocentral P3a appeared in the present study. This result is reasonable because the two types of visual stimuli after actions (i.e., *left* or *right*) were presented equiprobably and neither was novel nor distracting.

The most notable finding of the present study is that the LPP was larger in the choice condition than in the fixed condition, and this effect was observed both in the no instruction condition and in the count condition. The results suggest that action selection actually enhances the expectation of a specific action effect. Expectation of the forthcoming event is assumed to be held in working memory. Compared to the fixed condition, participants could hold the cue stimulus information more firmly in the choice condition. First, they had to memorize the type of cue stimulus precisely to select the correct button. Secondly, the selected action itself may have served as a memory aid to hold the cue stimulus information. Consequently, the expectation of the forthcoming stimulus would be greater or more specific when participants selected an action option, and the mismatch between the expectation and the actual stimulus would elicited a larger mismatch-related LPP.

The scalp topographic differences between the no instruction and count conditions suggest that additional processing required in the latter condition may elicit a second posterior positivity. When participants are required to perform an additional task on target stimuli detected, a P300 (P3b) is followed by positive slow waves, which may have a more posterior scalp distribution compared to the P3b (García-Larrea and Cézanne-Bert, 1998). The LPP in the no instruction condition showed a centroparietal scalp distribution similar to the typical P300 (P3b). The amplitude increase at posterior sites probably reflects the overlapping of a positive slow wave that is related to additional processing required in the count condition. The present experimental design cannot determine to which this second positivity is related, the counting task, the instruction of the occurrence of mismatch, or the fixed order of this experimental condition. In either case, what is crucial for our research question is the finding that action selection increased the mismatch-related LPP amplitude independently of the task relevance of action effects.

5. Conclusion

By recording ERPs, we demonstrate that people can detect the mismatch between the expected and actual action effects even when it is not relevant to the task. The cognitive mismatch is reflected in a posteriorly distributed positive ERP in a latency range of 500−700 ms, which probably consists of the P300 (P3b) and positive slow wave. In applied settings, the amplitude of this potential can be used as an index of the cognitive mismatch between a user’s expectation and an appliance’s response.

Footnote

[1] In this study, we deal with the mismatch between a participant's expectation and the actual action effect, not with the semantic mismatch between a cue stimulus (*L* or *R*) and the second stimulus (*left* or *right*). We predict that similar results will be obtained even when other stimuli without semantic connotations are used as the second stimuli.

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Figure

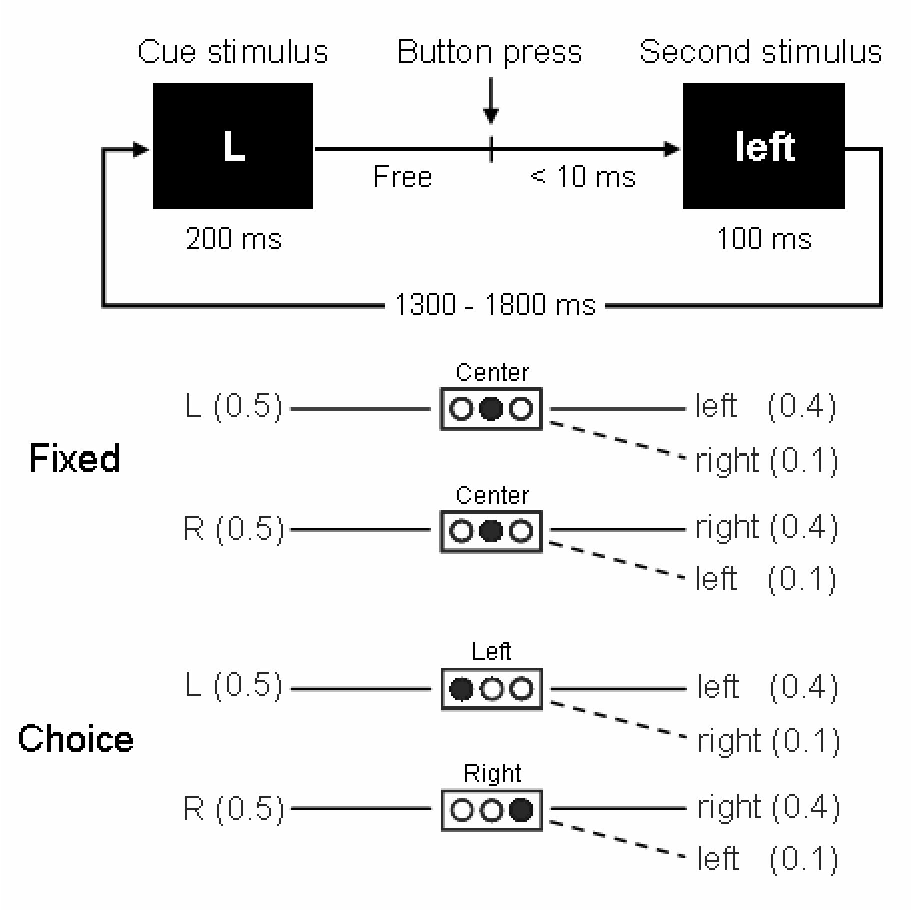

Figure 1. Time course and event sequence of each trial in the fixed and choice conditions. Participants pressed a button in response to a cue stimulus (either *L* or *R*, *p* = .50) at their pace. Within 10 ms after the button press, a second stimulus (action effect) was presented. In the fixed condition, participants were asked to press the center button regardless of the type of cue stimulus. In the choice condition, they were asked to choose the corresponding left or right button. The cue and second stimuli were matched in most trials (*p* = .80, solid lines), but sometimes mismatched (*p* = .20, broken lines). At the beginning of the experiment, participants performed these two conditions without being informed about the occurrence of mismatch (no instruction condition). Then, they were asked to perform the two conditions again while counting the mismatches silently (count condition).

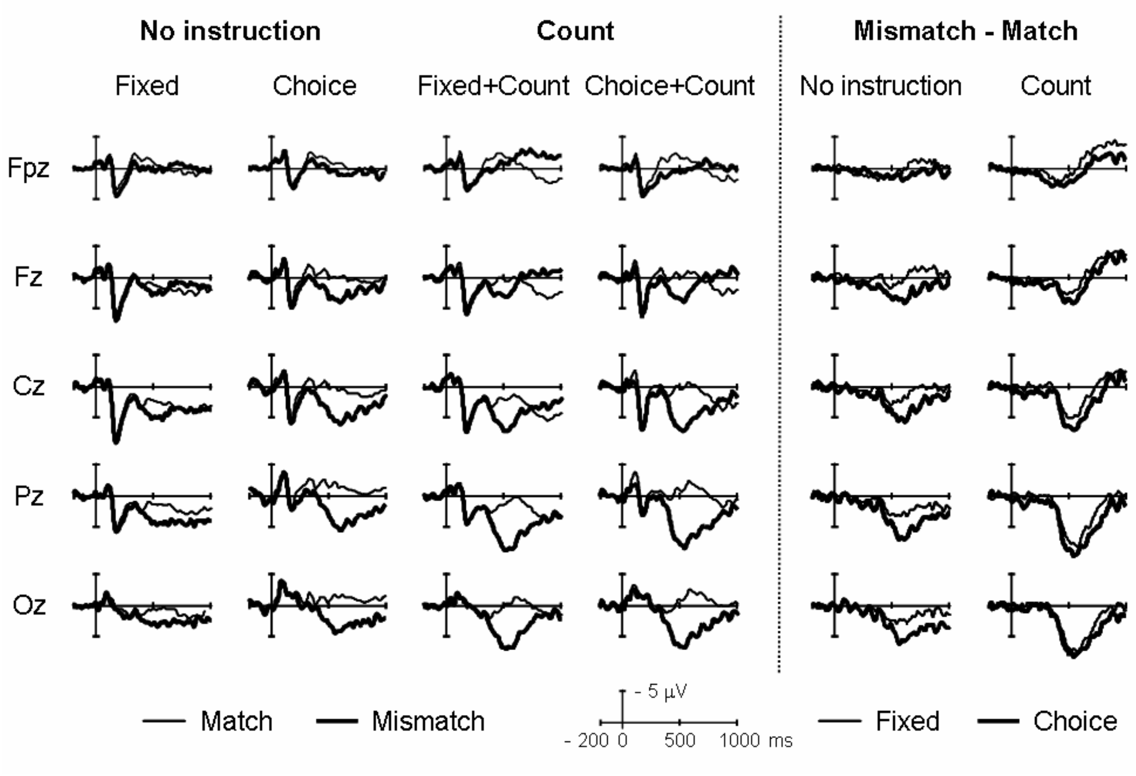

Figure 2. Grand mean ERP waveforms elicited by expected (matched) and unexpected (mismatched) stimuli after voluntary actions. The right panel shows difference waveforms that were calculated by subtracting the ERPs to matched stimuli from the ERPs to mismatched stimuli. Vertical lines indicate the onset of the second stimulus (action effect). In the difference waveforms, a late positive potential (LPP) appears as a large downward deflection in a latency range of 500–700 ms.

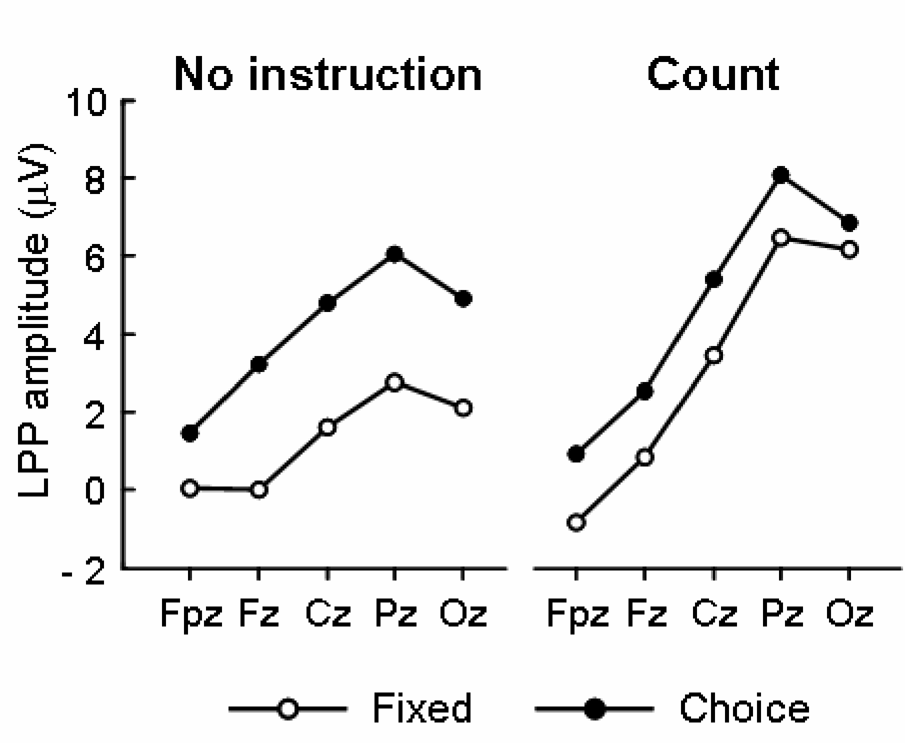

Figure 3. The mean amplitude values of the late positive potential (500–700 ms) calculated in the Mismatch–Match difference waveforms.

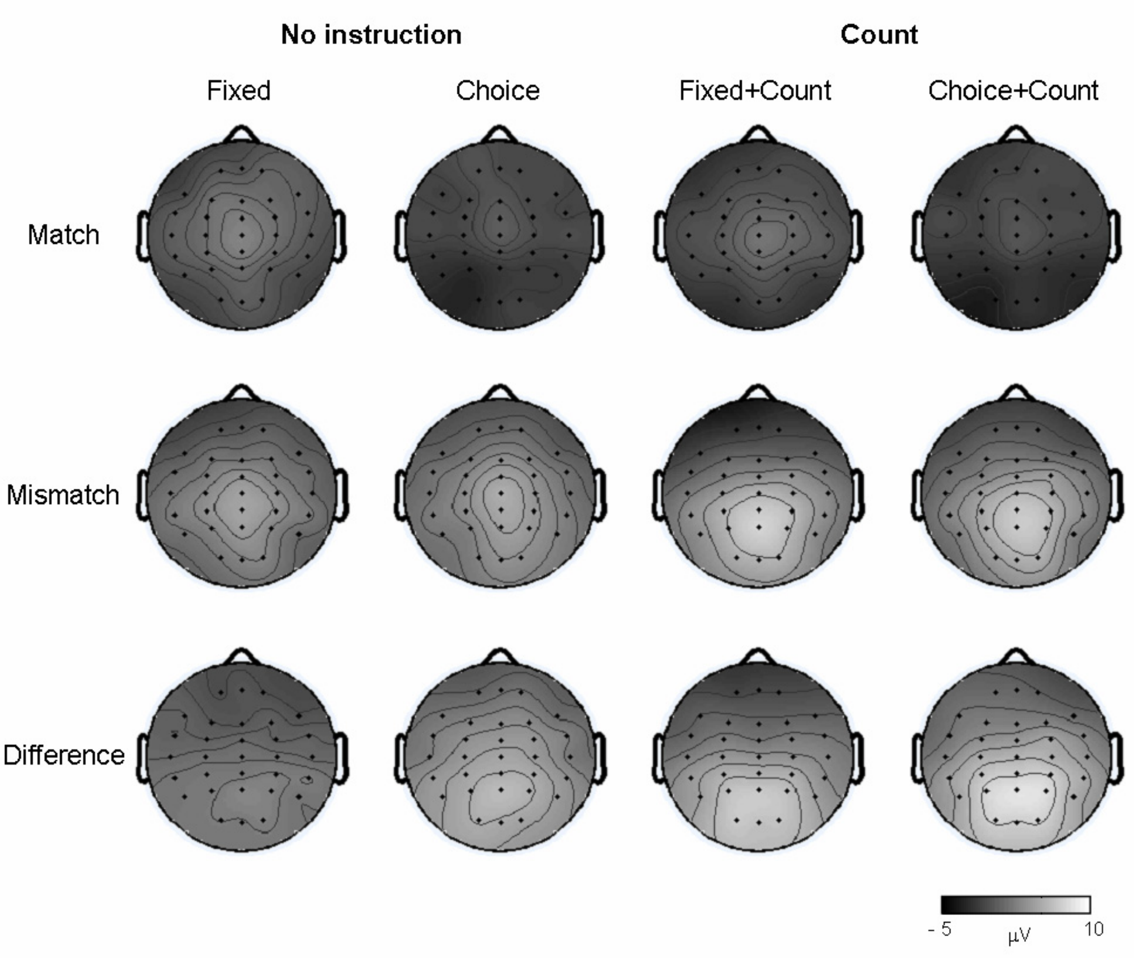

Figure 4. Scalp topographic maps of the mean amplitudes of 500–700 ms in all conditions.