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Electrocortical activity prior to predictable and unpredictable stimuli requiring a motor response

TÉRCIO APOLINÁRIO-SOUZA[1] | JULIANA O. PARMA[2] | VINÍCIUS R. CARVALHO[3] | MAICON R. ALBUQUERQUE[4] | GUILHERME M. LAGE[4*] | LIDIANE A. FERNANDES[5*]

[1] Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil.
[2] Auburn University, Auburn, United States.
[3] Electrical Engineering Post-graduation Program - Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil.
[4] Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil.
[5] Universidade Federal de Juiz de Fora, Governador Valadares, MG, Brazil.
* Guilherme Menezes Lage and Lidiane Aparecida Fernandes contributed equally to this work.

Correspondence to: Tércio Apolinário-Souza. Universidade Federal do Rio Grande do Sul – Escola de Educação Física, Fisioterapia e Dança. R. Felizardo, 750 - Jardim Botânico, Porto Alegre - RS, CEP. 90690-200.
Phone: +55 31 9.8843-8435
email: edf.tercio@hotmail.com
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HIGHLIGHTS

- Responses under an unpredictable context are slower than under a predictable context.
- CNV levels are similar between predictable and unpredictable context.
- Unpredictable stimuli became more predictable throughout practice.
- The identification of regularities in unpredictable conditions is not enough to achieve good performance. .

ABBREVIATIONS

CNV	Contingent negative variation
d	Cohen's d
EEG	Electroencephalographic
e	Electrode
f	Frequency
i	Log transformed signal (S) for every trial
η^2	Eta-squared
M_1 e M_2	Means of each condition (predictable and unpredictable)
PC	Predictable context
RT	Reaction time
S	Log transformed signal
SD_1 e SD_2	standard deviation of each conditio condition (predictable and unpredictable)
SS_{effect}	Sum of squares for a given effect
SS_{total}	Total sum of squares across all main effects, errors and interactions of the ANOVA
t	Trial
UC	Unpredictable context

PUBLICATION DATA

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BACKGROUND: The fronto-central slow-wave known as the contingent negative variation (CNV) is an electroencephalographic measure related to the ability of the motor system to extract spatial-temporal regularities to produce a motor response.
AIM: This study aimed to investigate the levels of electrocortical activity prior to predictable and unpredictable stimuli in a motor control task, and the association between CNV and reaction time (RT).
METHOD: Seventeen participants performed a task that consisted of removing the right index finger from the space bar as fast as possible after stimulus onset. All participants practiced under both a predictable (PC) and an unpredictable (UC) context.
RESULTS: Results indicated that RT under the unpredictable context was slower than under the predictable context. However, CNV levels under predictable and unpredictable contexts did not differ.
CONCLUSION: The certainty of stimulus appearance in the UC may have produced effects similar to those under the PC, resulting in similar CNV levels. However, the use of this mechanism under the UC was suboptimal to motor performance.

KEYWORDS: Motor Control | Attention | Biasing | EEG | Motor learning

INTRODUCTION

Many daily life situations require fast and accurate motor responses (Schmidt, 1968). Moreover, in some of these situations, it is possible to extract spatial-temporal regularities, decreasing chaos and unpredictability [1]. The ability to extract spatial-temporal regularities is paramount for the efficient orientation of our attention [2], but it has a high energetic cost that may not be afforded in every context [3]. Nonetheless, although the relationship between attentional control and the ability to extract spatial-temporal regularities can modulates motor responses [4,5], the nature of this relationship is still unknown.

One of the key points to better understand the nature of the relationship between attentional control and the ability to extract regularities is related to the comprehension of its underlying mechanisms [2]. These mechanisms include a cascade of neurocognitive processes that work together [5] and are controlled both by the top-down and bottom-up systems. The top-down system includes cognitive factors such as knowledge, expectations, and goals, while the bottom-up system includes factors like the intensity of sensory stimulation [6].

These neurocognitive factors involve the creation of an internal representation that enables inferences about the sensory consequences of the motor action to be performed [7,8]. When the gap between the internal representation and the actual sensory information is frequently small, the motor response tends to be programmed faster and can be, in some cases, anticipatory [9]. For instance, in a simple reaction time task (a single response to a single stimulus) in which a warning signal is followed by a foreperiod before stimulus onset, foreperiods with constant duration (e.g., 5 seconds) lead to simultaneous responses after a few trials [4].

The preparatory voluntary attentional activity which precedes the stimuli reflects the efficiency of the individual in extracting spatial-temporal regularities to generate a motor response [1,11]. The orientation of the voluntary attention involves the top-down system, since it is initiated in the medial frontal cortex and medial parietal areas [12], and facilitates the anticipatory biasing of the system toward task relevant information [7]. One of the electroencephalographic measures related to the orientation of voluntary attention is the contingent negative variation (CNV) [13,14]. The CNV is a fronto-central slow-wave negative deflection related to motor anticipation that occurs prior to stimulus onset [10,15.] Higher CNV levels are linked to the fronto-parietal processing system and is associated with the top-down system of attentional control [16]. Moreover, better motor performances are associated with increased CNV [10,6,17]. Figure 1 shows a hypothetical association between motor performance and CNV levels in the reception of a tennis service.

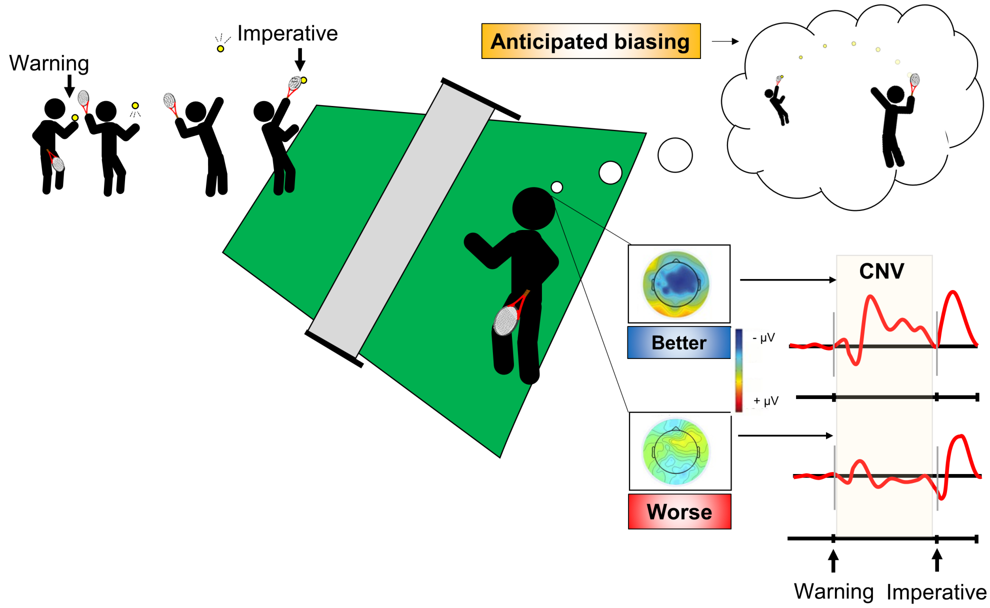

Figure 1. Association between motor performance and CNV levels in the reception of a tennis service. After the warning signal, as represented by the opponent's start of the tennis service sequence, there is an anticipatory biasing of the future features of the imperative stimulus. CNV occurs during this time interval, and a better performance is related to increased CNV levels.

Despite the well-known CNV behavior in contexts with regular and predictable stimuli, it is not clear whether the same type of CNV activity would be found in unpredictable contexts [8,18]. Radin et al. [18] manipulated different types of sound stimuli in an unpredictable way. They observed a CNV activity before the presentation of unpredictable stimuli that was similar to the CNV activity before predictable stimuli in other studies [12]. Although these studies suggest the presence of the CNV also in unpredictable contexts [8,19-21], predictable and unpredictable contexts have never been directly compared in a single experiment. Besides, previous studies have not analyzed the relation between CNV and motor performance. In other words, the quality of the generated motor response was never related to CNV levels in a predictable nor in an unpredictable context.

Since increased CNV levels reflect the efficiency of the ability to extract spatialtemporal regularities to generate a response [1,11], CNV levels are likely to increase across trials in a predictable context. On the contrary, unpredictable contexts hinder the efficiency of the extraction of spatialtemporal regularities [22], which may reduce CNV levels across practice. Therefore, we hypothesized that the CNV would be larger in predictable, as compared to unpredictable contexts, and these CNV levels would be related to differences in motor performance. Slower responses to unpredictable, as opposed to predictable contexts can be expected [10,16,17], but the relationship between the CNV and the responses generated in each context is unknown. Considering that the top-down system promotes the generation of fast responses, a stronger association between CNV and motor performance is likely to occur in predictable contexts.

In this study, we aimed to investigate the levels of electrocortical activity prior to predictable and unpredictable stimuli, as well as the association between CNV levels and motor performance in both contexts. Given that previous studies have not investigated the effects of the shift from a predictable to an unpredictable context on CNV, we expect a decrease in CNV levels right after the change in context, due to the top-down system becoming unable to use task relevant and regular information to anticipate motor response.

METHODS

Participants

Twenty healthy men (aged between 18 and 35 years) participated in this study. All participants were right-handed undergraduate students (laterality quotient of at least 80 points on the Edinburgh Handedness Inventory), novices to the experimental task, and had normal or corrected-to-normal vision. The sample size was defined using the software G*Power (version 3.1) and the CVN data from a pilot study. The software indicated a sample size of 16 subjects (critical F = 2.82) was required to achieve a 93% power. The experiment was conducted in accordance with the protocols approved by the Ethics Board from Universidade do Estado de Minas Gerais (CAAE 97208818.3.0000.5093). Written informed consent was obtained from all participants. Data from three participants were excluded from our analyses due to excessive EEG noise. Therefore, data from a total of 17 subjects were included in our final analyses.

Apparatus

A computer, a color computer screen, and a keypad were placed on a standard desk in the lab. Participants were asked to sit on a chair placed in front of the computer screen, and to adjust the keypad position to comfortably use it with their right-hand. Labview (National Instruments, Texas, EUA) and a custom-made software program (free access: https://github.com/edftercio/TimingClock) were used to control the experimental task. A 10 channel B-Alert headset (Advanced Brain Monitoring Inc., Carlsbad, CA, USA) was used to acquire the electroencephalographic (EEG) data. Nine Ag/AgCl EEG electrodes were placed over the F3, Fz, F4, C3, Cz, C4, P3, POz, and P4 scalp regions, according to the international 10–20 system. Two electrodes placed on the mastoid processes (left and right) were used as the reference and ground electrodes. All channels had a sampling rate of 256 samples/s and were connected in real-time via Bluetooth to a host computer, where the B-Alert software (Advanced Brain Monitoring Inc., Carlsbad, CA) stored and processed the EEG data.

Task

The motor task used was similar to the one used by Quesada and Schmidt [4]. The task consisted of removing the right index finger from the spacebar as fast and as accurate as possible after stimulus onset, that is, the stop of a clock hand presented on the computer screen (Figure 2). Each trial started when the virtual clock hand moved clockwise from the “zero” position in direction to the established goal (5 s, 4.92 s, or 2 s).

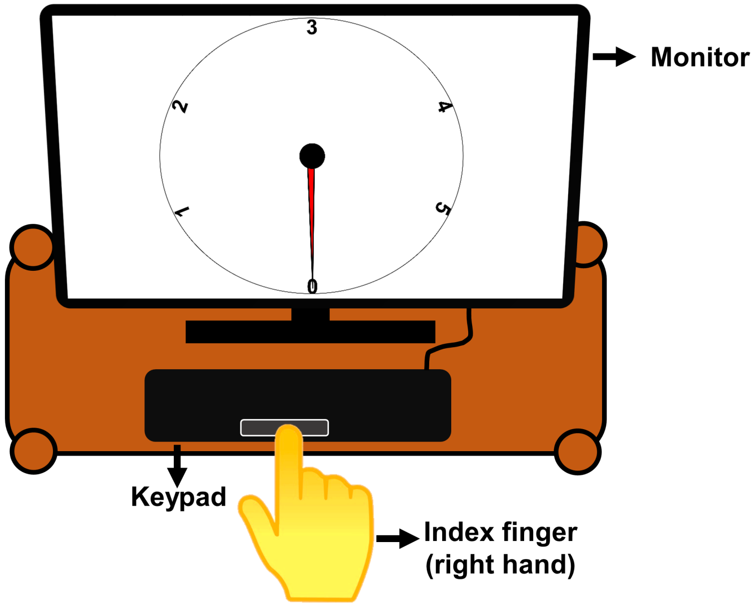

Figure 2. Motor task apparatus.

Procedures and design

All participants practiced the task under two conditions (Figure 3A). Initially, they practiced under the predictable condition, in which the clock hand stopped at 5 seconds in all ten trials. The unpredictable condition started immediately after the predictable condition. Before starting the second condition, participants were informed that now the stopping time could vary. In this condition, the clock hand stopped at 5 seconds on trials 1, 4, 5, 6, 8, and 10, at 4.92 seconds on trials 2 and 17, and at 2 seconds on trials 3 and 9 (Figure 3B).

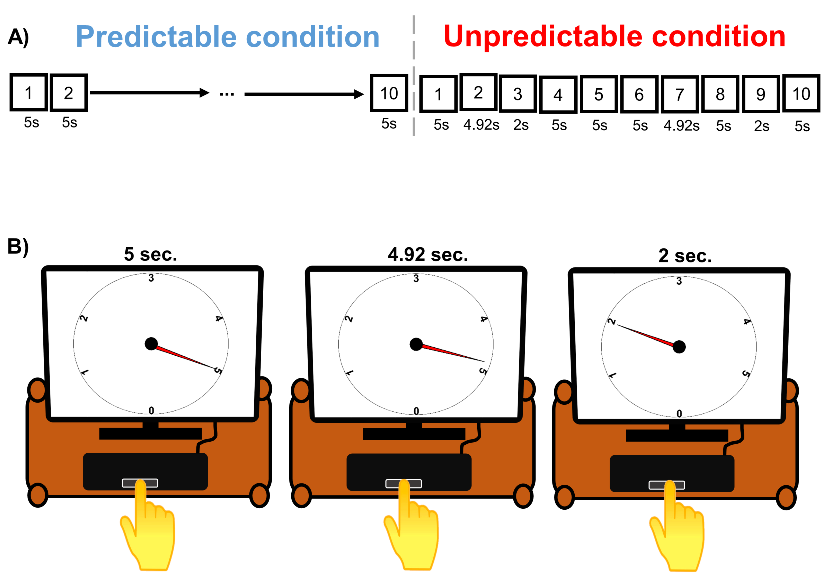

Figure 3. Procedures and experimental conditions. s = seconds; sec. = seconds.

EEG recording and preprocessing

We recorded EEG during all trials of both conditions (predictable and unpredictable). Before recording, impedance of all channels was adjusted to less than 60 kΩ. Bi-polar recordings (F3-F4, C3-C4, Cz-PO, F3-Cz, Fz-C3, Fz-PO) were selected to reduce the potential for artifacts generated by movements [23]. The EEG data were offline filtered using a 2nd order 0.1 high-pass Butterworth filter, and we removed the DC offset of the signal. Subsequently, independent components were extracted by using the Runica algorithm as implemented by EEGlab13.4.4 [24]. Epochs were extracted from –700 ms to 500 ms after stimulus onset. Epochs containing any remaining artifacts were detected using a moving window peak-to-peak threshold, with threshold of 100μV, window size of 200 ms and window step of 50 ms [25]. Finally, the signal was decomposed using a discrete Fast Fourier transform from 2 to 30 Hz with a resolution of 1 Hz. Subsequently, the log transformed signal (S) for every trial (i) was converted for every trial (t), frequency (f) and electrode (e) into a zscore[6] across conditions according to the following equation:

$$Z_{f,t,e}^{(i)} = \frac{S_{fte}^{(i)} - \mu_{fte}}{\sigma_{fte}}$$

To analyze CNV activity, we estimated the lower value prior to stimulus onset (from −700 to 0 ms) in each trial at Cz. We used Cz because literature indicates that this is the channel more closely associated with the CNV [26].

Data analysis

The performance-dependent variable used was reaction time. Reaction time corresponds to the time interval between the stimulus onset and the start of the movement. The reaction time (RT) data were log transformed (base 10) given the high level of variability across participants, as indicated by the coefficient of variation that exceeded 30% [27]. As a measure of preparatory voluntary attentional activity, we used the CNV, a slow-wave negative deflection that occurs prior to stimulus onset [15].

The RT and CNV were separately assessed in two analyses. First, the 10 trials of each condition were averaged together and compared to each other with a paired t test (predictable vs unpredictable). The second analysis consisted of a two-way repeated measures ANOVA [2 conditions (predictable vs unpredictable) x 20 trials]. These analyses were used to test the hypotheses that "slower responses in unpredictable than in predictable contexts can be expected" and "CNV would be larger in predictable as compared to unpredictable contexts", as indicated in the Introduction section.

In addition, the regression coefficients of the relationship between RT and CNV were also compared between conditions [6]. Coefficients were obtained through a linear regression model between RT and CNV for each participant. These coefficients were compared between conditions with a paired t test (predictable vs unpredictable). This analysis was used to test the hypothesis that “a stronger association between the CNV and motor performance is likely to occur in predictable contexts”.

The outlier analyses (intra-condition and intra-participant) were conducted for RT and CNV. Any datapoint lying outside of the range from the 3rd quartile + 1.5*interquartile to the 1st quartile – 1.5*interquartile would be considered an outlier. If outliers were detected, the outlier would be removed, then a new average would be calculated, and finally, the outlier datapoint would be replaced by the new average value. No outliers were found. An alpha level of .05 was chosen for all inferential statistics. Effect sizes were calculated using Cohen's (d) for t-tests and eta-squared (η^2) for ANOVAs. Cohen's d was calculated as follows:

$$d = (M_1 - M_2)/SD_{pooled}$$

$$SD_{pooled} = \sqrt{((SD_1^2 + SD_2^2)/2)}$$

where M_1 and M_2 are the means of each condition (predictable and unpredictable) and SD_1 and SD_2 are the standard deviation of each condition (predictable and unpredictable). A .80 is considered a large effect, a .50, is considered a medium effect, and an effect size of .20 is considered small (Cohen, 1988).

Eta squared was calculated as follows:

$$\eta^2 = SS_{effect} / SS_{total}$$

where SS_{effect} is the sum of squares for a given effect, and SS_{total} is the total sum of squares across all main effects, errors and interactions of the ANOVA (Rosner, 2011).

RESULTS

Behavioral results

Under the predictable condition, participants showed significantly faster RTs than under the unpredictable condition [$t(16) = -4.65$, $p < 0.001$, $d = 1.08$)] (Figure 4A). Moreover, a significant interaction was found between condition and trial [$F(9,144)=18.08$, $p < 0.001$, $\eta_p^2 = 0.53$)]. The post hoc analysis indicated that trials 2 to 10 had a significantly faster RT than the first trial ($p < 0.05$) under the predictable condition, while under the unpredictable condition the first trial had a significantly faster RT than the third and ninth trials ($p < 0.05$) (Figure 4B).

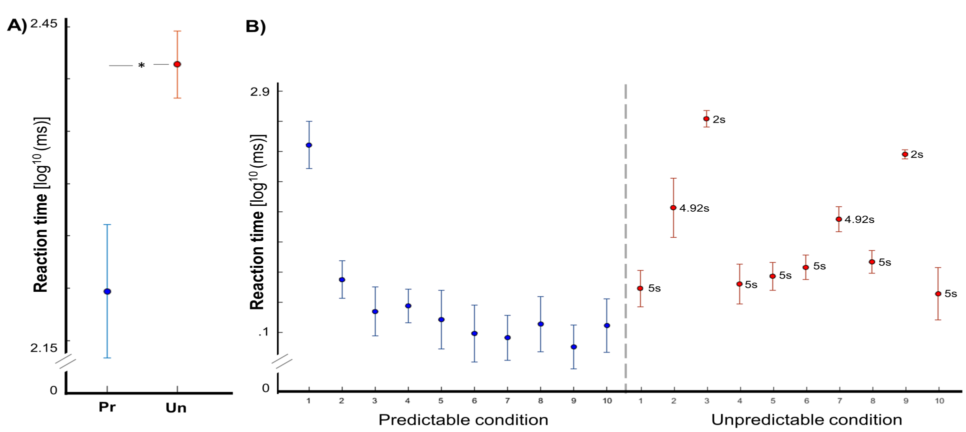

Figure 4. A) Mean and standard deviation for the reaction time under the predictable and unpredictable conditions. B) Mean and standard error for the reaction time of all 10 trials of the predictable and unpredictable conditions. Subtitle. Blue circle = predictable condition; Red circle = unpredictable condition; Pr = predictable; Un = unpredictable. In the right panel, the values next to each trial indicate the goal of each

trial of the unpredictable condition.

Electrophysiological results

The electrophysiological results did not show a significant difference between the predictable and the unpredictable conditions [$t(16)= -0.38$, $p = 0.70$, $d = 0.12$)] (Figure 5A). However, a significant interaction between condition and trial was found [$F(9,144)= 2.25$, $p = 0.02$, $\eta^2 = 0.12$)]. The post hoc analysis indicated that the CNV levels in the first trial were significantly larger than in trials five, six, seven, nine and ten under the predictable condition ($p < 0.05$), while under the unpredictable condition the CNV level in the first trial was significantly smaller than in trials three, four, six, seven and ten ($p < 0.05$). Moreover, the last trial of the predictable condition showed a higher CNV level than the first trial of the unpredictable condition ($p < 0.05$) (Figure 5B).

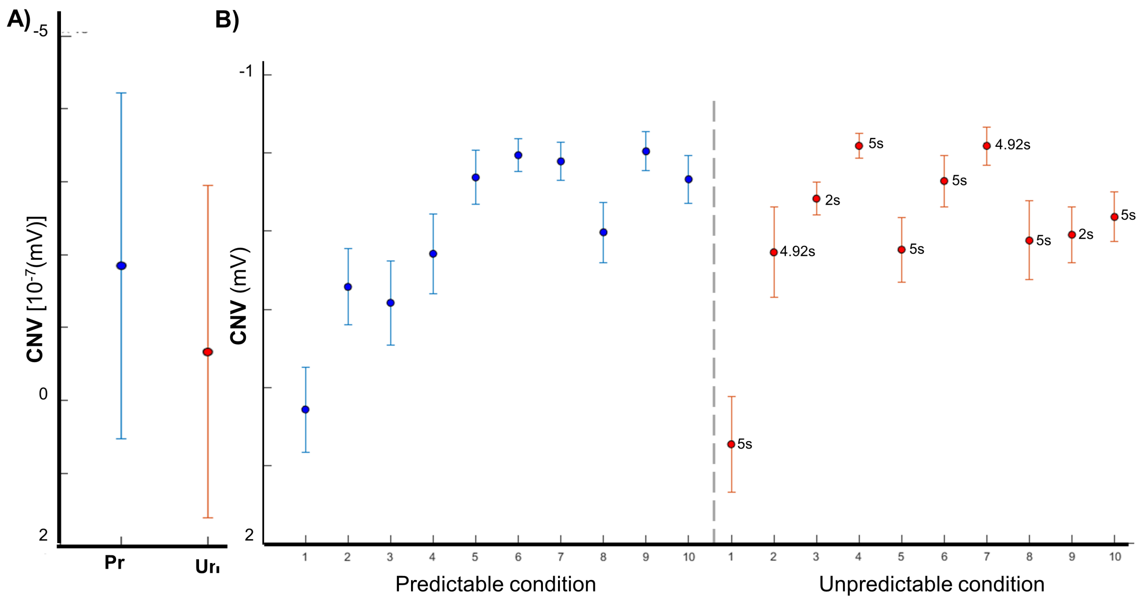

Figure 5. A) Mean and standard deviation for the contingent negative variation (CNV) under the predictable and unpredictable conditions. B) Mean and standard error for the contingent negative variation (CNV) of all 10 trials of the predictable and unpredictable conditions. Subtitle. CNV = contingent negative variation; Blue circle = predictable condition; red circle = unpredictable condition; Pr = predictable; Un = unpredictable. In the right panel, the values next to each trial indicate the goal of each trial of the unpredictable condition.

Linear model coefficients of the regression analyses

We observed a significant difference between the linear coefficients of the predictable and unpredictable conditions [$t(16)=4.21$, $p < 0.001$, $d = 1.40$)] (Figure 6A), in which the predictable condition showed stronger correlations than the unpredictable condition. Figure 3B shows a better adjusted value ($R^2 = 0.78$) for the relationship between CNV and RT in the predictable condition, as compared to the unpredictable condition ($R^2 = 0.03$). Moreover, there was a direct relationship between CNV and RT under the predictable condition (slope = 2.44), while there was an inverse relationship under the unpredictable condition (slope = -0.53).

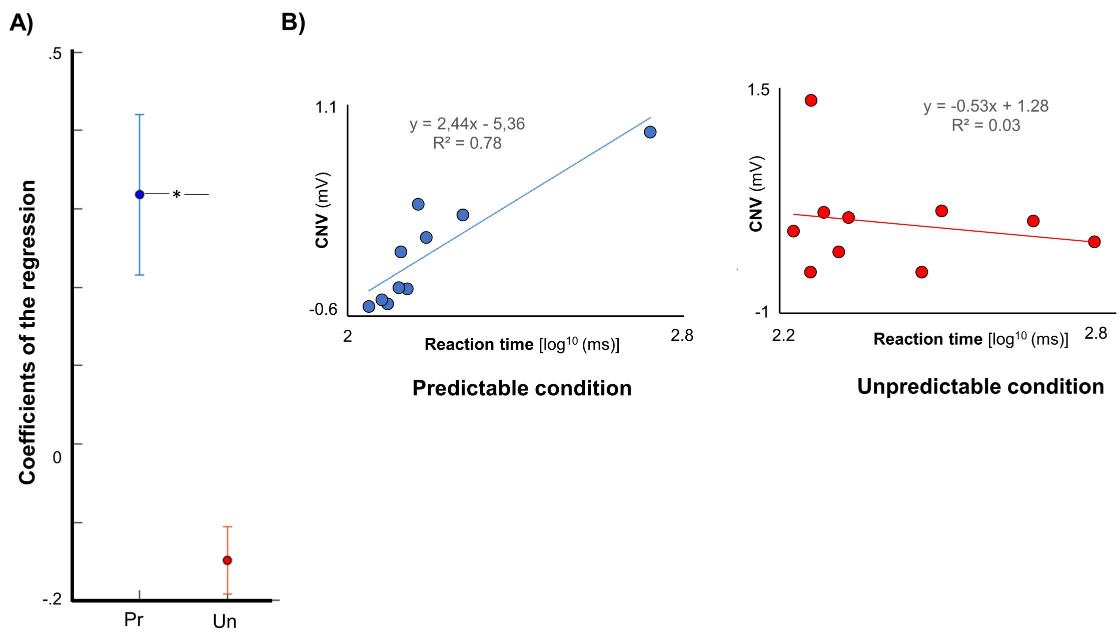

Figure 6. A) Mean and standard deviation for the linear coefficients under the predictable and unpredictable conditions. B) Correlation between reaction time and CNV under the predictable and unpredictable conditions. CNV = contingent negative variation; Blue circle = predictable condition; Red circle = unpredictable condition; Pr = predictable; Un = unpredictable.

DISCUSSION

The objective of this study was to investigate the level of electrocortical activity prior to predictable and unpredictable stimuli in a motor control task, and the association between CNV and motor performance in both contexts. As expected, responses under an unpredictable context were slower than those under a predictable context. We hypothesized that increased CNV levels would be found in the predictable condition, as compared to the unpredictable condition. This hypothesis was not supported by our results because, although the reaction times differed between conditions, the CNV levels were similar. On the contrary, our hypothesis of a stronger association between response time and CNV levels in the predictable condition than in the unpredictable condition was supported by our results, as well as our hypothesis of a decrease in CNV levels right after a shift in context. Although other studies have already investigated CNV levels in unpredictable contexts [8,18], this is, to the best of our knowledge, the first time a study investigates this context immediately following a predictable one, and the association between CNV and motor response quality in both contexts.

The faster motor responses under the predictable condition were expected given that the top-down control system acts to identify contextual predictability, anticipating the generation of fast and accurate responses [12]. Unpredictability delays specific processing stages, requiring more sensory information from the bottom-up control system [7]. Then, why were the CNV levels similar between different contexts? The focus of our study was on the predictability or unpredictability of the timing of the imperative stimulus. However, it is also possible to focus on the predictability (or unpredictability) of the occurrence of the imperative stimulus. In this regard, studies show that the uncertainty of the appearance of the imperative stimuli leads to decreased CNV levels [8,19-21]. It is possible that even in an unpredictable context related to onset timing, the certainty of occurrence of the imperative stimulus leads to allocation of attention processes via a top-down system. This type of cognitive control involves knowledge and expectation.[7] Therefore, the certainty of stimulus occurrence may have resulted in effects similar to those in the predictable condition. This hypothesis is supported by our results, since there was an increase in CNV across trials under the unpredictable condition. This result may indicate that the unpredictable stimuli became more predictable throughout practice, at least in terms of perception. In other words, with practice, the state of unpredictability can decrease.

The lack of differences between CNV levels under predictable and unpredictable timing of stimulus onset is a novelty of our study. Previous studies had indicated the presence of the CNV under unpredictable contexts [8,18-21], but had not directly compared CNV levels to predictable contexts. Higher CNV levels are associated with a better motor response [6,10,17]. However, our results showed that, when these contexts are analyzed together, a strong association is only found for the predictable context. It seems that the relationship between CNV levels and motor performance is only found in predictable and learnable conditions. The high CNV levels generated in the unpredictable condition due to the expectation of stimulus occurrence, do not entail good performance. This result is another piece of evidence showing that the unpredictable stimuli became, at least in perceptual terms, more predictable throughout practice. Participants identified regularities in this condition, hence the increased CNV levels, but this information was not enough to result in good performance.

The only factor that reduced CNV levels when shifting conditions was the one Tesse [28] calls the "social effects". A simple instruction referring to the omission or change in the imperative stimuli can affect or extinguish the CNV. Studying the CNV can be of great value for studies on social communication [14]. The instruction given to participants that the task would be modified between the 10th trial of the predictable condition and the 1st trial of the unpredictable condition led to decreases in CNV levels. Social effects were found in recent studies [8]. In Duma et al. [8], the simple information that there would not be an imperative stimulus (car collision) during task familiarization resulted in lower CNV levels as compared to the CNV levels of when the stimulus was present. The authors suggested that the expectation created by the explicit instruction about the change in context led to increased CNV levels.

Another explanation to the results entailed by the explicit instruction arises from the model proposed by Grent-'t-Jong and Woldorff [12]. In this model, a temporal cascade of processes starts with activity in the frontal eye field, which is followed by activity in medial parietal regions. This joint activity maintains the priming activity in the visual sensory cortex. This mechanism is selected through the orientation of attention to sensory features in the environment [12]. In this regard, the explicit instruction about a possible change in context would have resulted in an increased demand of the sensory processing of the current condition, activating the bottom-up system and decreasing the activation of the fronto-parietal network related to CNV [7]. However, this possibility must be further addressed with a specific study design.

Although the performance in the last trial of the predictable condition was not different from the performance in the first trial of the unpredictable condition, their CNV levels differed. It is possible that, under a condition different from the usual, the attentional preparatory activity via fronto-parietal network is not a paramount mechanism for good performance [29-31]. The increased demand of sensory information in the current condition may be one of the main mechanisms of good performance in unpredictable conditions [12,31] Under this condition, the individual requires more from external information about the current context than from information related to an internal representation (anticipatory) [7]. In this regard, the possibility of change in the task context likely induces the system to adopt this type of processing to maintain a performance similar to that of the predictable condition.

CONCLUSION

In this study we aimed to investigate the level of electrocortical activity prior to predictable and unpredictable stimuli in a motor control task, as well as the association between CNV levels and motor performance under both contexts. Our results suggest that making the timing of appearance of the imperative stimuli unpredictable leads to effects similar to those entailed by predictable contexts. However, adopting this strategy was not efficient to generate motor responses under an unpredictable context. These findings deepen our understanding of the electrocortical activity expected prior to predictable and unpredictable stimuli, and its relation to motor performance, as proposed by Walter et al.[14].

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