Evidence for a decision making process at the cortical level during adaptation to changing loads

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Abstract

Movement-related potentials (MRPs) recorded from the scalp are the electrical signals generated by the brain related to the generation of voluntary movement. These potentials have been shown to vary due to the force exerted by subjects as well as their familiarity with the task. It has recently been shown that when a subject adapts to a new motor task, the power of MRPs does not change monotonically, but instead there appears a large increase in its power after several repetitions of the task. This increase is most evident in MRPs recorded from locations over the prefrontal cortex. In this study we investigate how this peak of activity is related to task parameters. Six subjects were asked to perform a motor task which required adaptation. By changing the number of alternative loads that appeared in the experiment and their type, we were able to show that both the number of task executions before the appearance of the peak of activity as well as its power are related to the number of loads the subjects knew were possible. This may suggest that the peak of activity is a manifestation of a decision making process designed to estimate the parameters of the current task.

1 Introduction

Control of voluntary behavior is achieved through an interaction of forward control, where the action is based on an internal model of the load, and feedback, which corrects the errors caused by the mismatch between the internal model and the real world [20]. The main drawbacks of feedback are that it inherently takes longer to act due to delays in the feedback loop, requires attention by the brain, and usually involves greater expenditure of energy[9]. Thus, it is advantageous to perform as many tasks as possible using automatic, forward control.

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Forward control is guided through the use of an internal model [9],[19]. The shift to the use of an internal model is characterized externally by decrease in the stiffness of the limbs [9],[18] and smoother movements [8].

New movements are initially carried out with the attention of frontal cortical areas of the brain. The prefrontal cortex (PFC) has been specially noted for its role in such actions [16]. After repeated performance of the task there is a shift from this intentional control to automatic movements [19] carried out using other areas of the cortex, mainly the premotor, posterior parietal and cerebellar areas of the cortex. This is evident in both new types of movement, where the process taking place is one of learning [21], as well as when only the parameters of the environment have changed, and thus only adaptation is necessary.

It is important to define at this point the difference between adaptation and learning. In this article we define adaptation as the adjustment of the subjects' motor actions to the environment [10], as opposed to learning which is used to describe the process of creating and establishing a new skill.

The performance of people on a novel motor task, at least for voluntary movements, has been shown to improve gradually over time [9]. Thus, it was interesting to discover if such a pattern of activation would occur at the cortical levels. This could be investigated by examination of movement-related potentials (MRPs). MRPs are components of the electroencephalogram (EEG) related to voluntary movement. These potentials have a well-known morphology that has been studied under a variety of experimental conditions (See, for example, [6],[12]).

Unfortunately, MRPs are recorded at an unfavorable signal-to-noise (SNR) of approximately -15dB. The noise contaminating MRPs stems from both ongoing electroencephalographic (EEG) activity as well as facial electromyographic (EMG) signals [1]. The conventional method of recovering MRPs is by synchronized averaging of a large number of single-trials (see, for example, [6],[13]). Because of this, it is difficult to study short-term variability associated with learning and problem solving.

Over the years, many algorithms were proposed for the detection of trial-to-trial variability in components of EEG [14],[2],[3]). Most of these algorithms work well for cognitive evoked potentials with a non-negative SNR, but fail when applied to MRPs which have a highly negative SNR. The few algorithms that do perform well for MRPs usually rely heavily on the average MRP [4],[14]). Recently [21] we proposed using a modified version of the matching pursuit algorithm [5] in order to remove most of the noise from MRPs. This method has been shown, through simulations, to remove up to 12 dB of the noise. Thus, this method makes it possible to observe changes in MRPs by averaging only few repetitions of MRPs. Therefore, using this method makes it possible to observe the changes in activity at the cortical level which occur during adaptation to a new environment.

As noted above, the performance of people on a novel motor task, at least for voluntary movements, has been shown to improve gradually over time and use less energy [9]. Thus, it was not unreasonable to assume that similar behavior would occur at the cortical level. However, in a recent study [21] we have shown that this is not the case. Instead, after several attempts at performing a task, a significantly higher level of activity in MRPs appears during the performance of the task. This level of activity decreases to a baseline level immediately afterward. This activity appears to be strongest in the PFC. Following this evidence, a recent study [15] confirmed the results found in that initial work [21], and also found that if adaptation was impossible, no activity peak appeared.

In this study we attempt to test the dependence of the temporal location (i.e. the number of task repetitions) and amplitude of the peak on experimental parameters. We show that the temporal location of the peak and its' amplitude are dependent on the number of alternative loads users thought they would be presented with. These findings, coupled with evidence from other studies, suggest that adaptation to a changing environment is dependent on performing a critical number of movements. We hypothesize that this is due to a decision-making process in the brain in which the correct response to a new task is chosen.

2 Materials and methods

2.1 Experimental protocol

Six subjects (four males and two female aged 25 to 45 years old) participated in the study. The subjects did not suffer from neurological or muscular disorders. Informed consent was obtained from the subjects prior to the experiment.

2.2 Procedure

The subject was seated on an armchair, approximately perpendicular to a lever attached to a vertical rod. Subjects held the vertical rod using their right hand and used their right index finger to pull the lever. The load needed to pull the lever was changed by controlling a motor connected to the lever. A micro-switch was used to sense the beginning of the lever's movement.

Changing the type and intensity of the feedback current to the motor under the lever controlled the load needed to pull the lever. Thus, feedback relative to the lever position generated spring-like loads and feedback relative to the lever velocity produced viscous resistance. Before the beginning of each experiment, the subjects were told the number of different loads they could expect to encounter during the experiment, and their type, e.g.: Two levels of spring loads and two levels of viscous loads.

Each experiment was divided into several recording runs, which lasted 45 seconds. Before each recording run the parameters for generating one of the possible loads were fed to the motor. The subject was then instructed to pull the lever, self paced, as quickly as possible, pausing approximately 3 seconds between each pull. Before the beginning of each run the load pulling the lever was changed randomly, but the subject could not feel the new load until the first pull of the lever. At least five recording runs from each of the loads possible in an experiment were recorded. A schematic diagram of the experimental procedure is given in figure 1.

It is important to note that although subjects made recording runs with only a limited number of values, the loads had to be learned anew at the beginning of each run. This is because during such short recording runs subjects cannot remember more than one, current, load [11].

The subjects were asked to perform experiments where they could be presented with one, two, four, or six possible loads from each of the load types. Each subject performed between one and four experiments, each experiment consisting of a different number of possible loads. The experiments were carried out at different times so as to minimize subject fatigue. One subject sat in an experiment where there were eight spring loads possible, and in an experiment where the subject was told the maximum number of possible loads, but the actual number was smaller than the maximum number given to him.

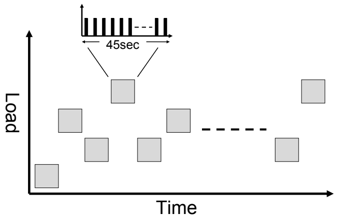


Figure 1: A schematic diagram of the experimental protocol. In this diagram the described experiment is one where four possible loads were presented to the subject. The subject performed self-paced movements against a given load level in 45 second experimental blocks. The loads were changed randomly before the beginning of each block.

2.3 Recording procedure

Cortical potentials were recorded using electrodes placed over F_P1, F_P2, F_3, F_4, C_3, and C_4, all referenced to an electrode over C_z (according to the international 10-20 system, using an Electro-Cap). The surface electromyogram (EMG) signal was recorded by placing a pair of electrodes over the forearm of the right hand and amplifying the electrical potentials between them. The electrodes were Ag-AgCl surface electrodes, circular, with a 6-mm diameter. Resistance between electrodes was less than $5K\Omega$. The state of the lever (stationary or non-stationary) was recorded in order to synchronise the MRPs.

The EEG and EMG channels were amplified using a custom made optically isolated amplifier with a gain of 10,000 and 0.01-40Hz pass band. The amplified signals were digitized and sampled, together with the lever state, at 250Hz using a PCI-DASK 9118HG 12-bit analog to digital converter card on a PC. Custom-made data acquisition software was used to drive the sampling card and store the data on hard disk.

2.4 Data processing

The data was segmented into single trials from 1.5[sec] before the beginning of the levers' movement, until 1[sec] after it (a total of 625 samples). Trials with peak-to-peak amplitude larger than $50\mu V$ in frontal channels were rejected so as to exclude trials containing electrooculographic (EOG) noise.

The movement time was calculated by measuring the delay between the beginning of the levers' movement until it was completely closed. The EMG power associated with a given movement was computed by calculating the integral of the rectified EMG signal from 300mSec before the beginning of the movement until 200mSec after it, after high-passing it at 20Hz. This filtering was necessary so as to reduce movement artifacts.

MRPs were first denoised using a recently-proposed, modified version of the matching pursuit algorithm, which used a dictionary pruned so as to typify the noise. A detailed description of this algorithm and simulations of its' performance on synthetic data is given in [21]. The MRPs are denoised by passing them through several iterations of the matching pursuit algorithm, a process which removed approximately 12dB of the accompanying noise. After denoising, the MRPs were averaged according to the serial number of the lever pull in a recording run, which corresponds to the adaptation to the load during the specific run. As stated above, the load is changed before each recording run. The subject cannot know what the new load is before the first pull of the lever, and needs to learn it anew during every recording run. Thus, the serial number of the lever pull is consistent with changes in the MRP due to adaptation to the load during a recording run. At least 20 MRPs were averaged for each serial lever pull.

3 Results

Figure 2 shows a sample signal during the various stages of processing, from the original, noisy, MRP, via the denoising process, until that MRP is averaged with other denoised MRPs to show the peak of activity. In this specific demonstration, the experimental setup was producing four values of a spring-type load. Note that for the purpose of conforming with previous studies of MRPs, we have negated all MRPs and they are thus are shown as positive waveforms. However, all recoded MRPs showed a negative trend.

Our first experiments were made in order to determine if both the types of loads (i.e. viscosity and spring) and the number of loads of each type influence the temporal location of the peak of activity. For this goal, we asked subjects 1 and 5 to perform experiments with one or two types of loads, for which one or two values of each load were available. These experiments revealed that the temporal location of the peak was independent of the types of loads present in the experimental system, and only depended on the number of different values possible from each type of load.

Also validated in these first experiments was a finding from our previous study [21] that the above-mentioned peak of activity was most pronounced in data recorded from prefrontal locations (F_P1, F_P2). Indeed, no significant activation in data recorded from other channels could be related to the temporal sequence of events. We therefore performed the remaining experiments in order to test how the temporal location of the peak of activity depended on the number of loads available in the system. Figure 3b shows the results from these experiments as seen in data recorded from location F_P1. This figure demonstrates a clear correlation between the number of loads and the location of the peak ($R^2 = 0.6794, p < 0.0001$).

The relation between the temporal location of the peak and its' relative power in data recorded from channel F_P1 is shown in figure 3b. In this figure the power of the peak is divided by the average power of the MRPs from repetitions one through ten. This is done in order to enable testing across subjects, who can have different levels of activation. As figure 3b shows, there is positive correlation ($R^2 = 0.297, p = 0.0237$). Although statistically significant, this relation is not very strong, but it should be noted that the MRPs used to produce this figure were not completely clean of noise, and thus it is probable that noise contributed to some degradation in the match between the peak location and its power.

Finally, we attempted to examine if the temporal location of the peak of activity depended on the number of loads the subject thought were present in the experimental system or on the actual number of loads. Subject 1 was asked to repeat the task, and initially he was told that there were eight possible spring-type loads. In reality, only four loads were presented by the experimental system. After five recording runs of each load, the subject was told that only four loads were present in the system, and another five recording runs of each load were performed. The peak of activity in the first recording runs appeared after 7 repetitions of the task,

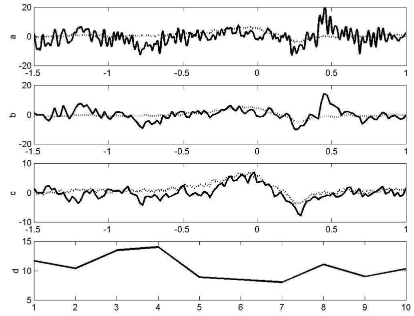
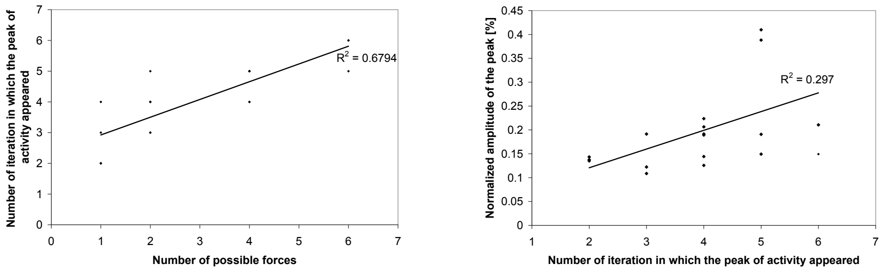


Figure 2: A typical MRP shown during the stages of processing. Figure (a) shows a sample MRP and an average of 100 MRPs (dotted). Figure (b) shows the same MRP after the denoising process, compared to an average of the same 100 MRPs after denoising (dotted). The average of 10 denoised MRPs compared to the average of 100 raw MRPs is shown in figure (c). It can be seen that the match between the two is good, suggesting that the denoising process does not cause a large distortion of the signal. Finally, figure (d) shows the power of the MRPs as a function of the iteration number in which they were generated (See text). The peak of activity in this specific figure is evident at iteration 4, although the power of the MRPs in iteration three is also significant. The horizontal scale in figures (a)-(c) is time in seconds, zero time marks the beginning of movement. The vertical axis in these figures is negative amplitude in μV. The horizontal scale in figure(d) is the serial number of the lever movement, and the vertical axis is the power of the MRPs, in $10 - 12 \mu V^2$. All data in this figure was recorded from location F_{P1}.



(a)

(b)

Figure 3: Figure (a) shows the temporal location of the peak of activity versus the number of possible loads in the system. Figure (b) shows the normalized amplitude of the peak of activity versus its temporal location. These figures, plotted using data from the six subjects and all experimental conditions, recorded from location F_{P1}, shows that there is significant correlation (R^2 values shown on the graphs) between the timing of the peak of activity and the number of loads with which the subject was presented as well as between the amplitude and timing of the peak of activity recorded from electrodes over the prefrontal cortex. There are a total of 17 points in these graph.

corresponding to eight available loads. The peak of activity in the last recording runs appeared after 5 repetitions of the task, corresponding to four loads. Thus, it seems that the temporal location of the peak of activity depends on the number of loads the subject thought there were in the system, rather than on the actual number of loads present.

4 Discussion

It has previously been shown that adaptation to simple motor actions, as reflected by activation of prefrontal regions of the cortex, is not a monotonous process. Instead, after several repetitions of a task that requires adaptation, a high level of activity appears during one repetition. Based upon the studies quoted in the introduction and the findings reported in the results section of this paper, it is possible to summarize the known facts regarding this peak of activity.

First, if adaptation is impossible, such as when the load is changed after every pull of the lever, no peak of activity appears [15]. Anatomically, the peak of activity appears over the prefrontal regions of the cortex. Morphologically it is most likely that the peak of activity is the result of increase in activation during movement execution and movement comprehension [21]. The temporal location of the peak is independent of how many different types of loads are presented to the subject, and is highly correlated with the number of values that each type of load can have in the system. Thus, for example, if for a given subject and three possible loads the peak of activity appears after the fourth pull of the lever, we can predict that it will appear after five pulls of the lever when the subject is presented with four loads. Furthermore, it appears that the timing of the peak is correlated not with the actual number of loads but with the perceived number of loads.

Figure 3 shows that the temporal location of the peak is correlated with its energy. If the peak of activity is related to a decision-making process, as we assume, such a correlation is likely to appear since when more options are possible, the decision making process can be expected to longer and more difficult.

The peak is not correlated with the speed of movement, and seems to appear immediately after EMG activity reaches its' lowest level for performing the task [21]. Finally, there is good correlation between the temporal location of the peak and its' power.

These findings have led us to suggest that the peak of activity is the manifestation of a decision-making process related to the task. Once such a process is finished the subject might be able to switch from feedback control, based on a rough estimate of the load, to feedforward control. The forward control is based on parameters that can be estimated when enough information about the load was collected while performing repetitions of the task.

It is interesting that we were unable to find a maximum value for the temporal location of the peak of activity. Further experiments are needed to verify if such a maximum exists, although this is by no means guaranteed [17]. We suggest that the effect described in this article is one where enough data needs to be gathered before the task can be solved. This effect is documented in philosophical literature[7], but we believe this is one of the first instances that this effect is directly evident in the activity of the brain. However, further research is required in order to establish the phenomena in additional subjects.

References

[1] M. Akay and J.E. Daubenspeck. Investigating the contamination of electroencephalograms by facial muscle electromyographic activity using matching pursuit. *Brain and Language*, 66:184–200, 1999.

[2] E.A. Bartnik, K.J. Blinowska, and J.P. Durka. Single evoked potential reconstruction by means of wavelet transform. *Biological Cybernetics*, 67:175–181, 1982.

[3] G.E. Birch, P.D. Lawrence, and R.D. Hare. Single-trial processing of event-related potentials using outlier information. *IEEE Transactions on Biomedical Engineering*, 40:59–73, 1993.

[4] S. Cerutti, G. Chiarenza, D. Liberati, P. Mascellani, and G. Pavesi. A parametric method of identification of single-trial event-related potentials in the brain. *IEEE Transactions on Biomedical Engineering*, 35:701–711, 1988.

[5] G. Davis, S. Mallat, and Z. Zhang. Adaptive time-frequency approximation with matching pursuits. *Proceedings of the SPIE*, 2242:402–413, 1994.

[6] L. Deecke, W. Becker, B. Grozinger, P. Scheid, and H. Kornhuber. Human brain potentials preceding voluntary limb movements. *Electroencephalography and Clinical Neurophysiology*, 33:87–94, 1973.

[7] L. Goetz. *The creative cumulation.* Philosophical Society, Tel-Aviv, Israel, 1951.

[8] A. Hreljac. The relationship between smoothness and performance during the practice of a lower limb obstacle avoidance task. *Biological Cybernetics*, 68:375–379, 1993.

[9] G.F. Inbar and A. Yafe. Parameter and signal adaptation in the stretch reflex loop. *Progress in Brain Research*, 44:317–337, 1976.

[10] A. Karniel and G.F. Inbar. Human motor control: Learning to control a time-varying non-linear many-to-one system. *IEEE Transactions on Systems, Man, and Cybernetics C*, 30:1–11, 2000.

[11] A. Karniel and R.A. Mussa-Ivaldi. Does the motor control system use multiple models and context switching to cope with a variable environment? *Experimental Brain Research*, 143:520–524, 2002.

[12] B. Kopp, A. Kunkel, G. Muller, W. Mohlnickel, and H. Flor. Steady-state movement-related potentials evoked by fast repetitive movements. *Brain Topography*, 13:21–28, 2000.

[13] R. Kristeva, D. Cheyne, W. Lang, G. Lindinger, and L. Deecke. Movement-related potentials accompanying unilateral and bilateral finger movements with different inertial loads. *Electroencephalography and Clinical Neurophysiology*, 75:410–418, 1990.

[14] D.H. Lange and G.F. Inbar. Modern techniques in erp research, 1999.

[15] I. Makienko. Estimation of single movement-related brain potential components with changing loads. *M.Sc. Thesis, Faculty of Electrical, Technion, Israel Institute of Technology*, 2001.

[16] E.K. Miller and J.D. Cohen. An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, 24:167–202, 2001.

[17] G.A. Miller. The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, 63:81–97, 1956.

[18] T.E. Milner and C. Cloutier. Compensation for mechanically unstable loading in voluntary wrist movement. *Experimental Brain Research*, 94:522–532, 1993.

[19] T.E. Milner and C. Cloutier. Neural correlates of motor memory consolidation. *Science*, 277:821–825, 1997.

[20] R. Shadmehr and A. Mussa-Ivaldi. Adaptive representation of dynamics during learning of a motor task. *Journal of Neuroscience*, 14:3208–3224, 1994.

[21] E. Yom-Tov, A. Grossman, and G.F. Inbar. Movement-related potentials during the performance of a motor task 2: Cerebral areas activated during learning of the task. *Biological Cybernetics*, 85:387–394, 2001.