What happens to the readiness potential when the movement is not executed?

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The purpose of this study was to investigate and compare the movement-related brain potentials recorded from two groups of right-handed male study participants. One of the groups prepared for and conducted repetitive toe movements while the other prepared to carry out the same type of movement but finally did not execute it. The readiness potential, premotion positivity, motor potential and reafferent potential were recorded from 20 electroencephalogram electrodes. The most salient result was the greater readiness potential amplitude discovered in participants who ended up carrying out the movement, which indicates that the level of preparation in a repetitive task is greater when a final response is required. No group differences were found for the other potentials.

Keywords: event-related brain potentials, motor systems, readiness potential

Introduction

A number of movement-related brain potentials were discovered and described by Kornhuber and Deecke in the mid 1960s [1]. The first of these waves was the readiness potential (‘bereitschaftspotential’), which is an indicator of the neural activity associated with the preparation to carry out a movement. It is a gradually increasing negative trend that starts a few hundred milliseconds prior to the movement [1]; the exact time (e.g. 1700 ms) is dependent on the interval between movements. Some authors [2–4], although not others [1,5], have differentiated a bilaterally symmetrical readiness potential from a late negative shift that usually shows a contralateral preponderance in upper limb movements. The readiness potential reaches its maximum amplitude before a small premotion positivity. This premotion positivity occurs about 100 ms before electromyogram onset [6], which is followed by an abrupt and negative motor potential [7]. The motor potential starts before the movement, although it usually presents its maximum amplitude over central electrodes after electromyogram onset. The motor potential reflects the corticospinal output that starts the motor act [1]. Finally, this sequence of waves ends with the reafferent potential. Owing to the fact that this last potential occurs after both active and passive movements, the reafferent potential is considered to be a correlate of somatosensory information that reaches the cerebral cortex [8].

The readiness potential is usually maximum over the vertex and shows two interesting characteristics: (1) it can be recorded in preparation to specific movements even when the movement is vetoed [9], and (2) it is lateralized with respect to the contralateral hemisphere in the case of finger movements and with respect to the ipsilateral hemisphere in the case of toe movements. This peculiarity is owing to the orientation of the neural generators or anatomical organization of the motor cortex [10]. Although consistency in the feature of lateralization has been somewhat limited [11], the dipole orientation explanation seems to be on the whole suitable to account for most discrepancies.

Taking these more recent findings into consideration, the aim of the present study was to elaborate on the differences that can be detected in the brain electrical activity of participants who prepared to carry out a specific movement and executed the movement compared with that of participants who prepared to carry out the same motor act but did not execute it. Focusing not just on the readiness potential but on subsequent potentials as well, it was hypothesized that to conduct abrupt toe movements would have its maximum manifestation on the motor potential, the amplitude of the motor potential being greater in those cases where the movement was carried out. In addition, on the basis of the specific neuronal generators of the movement-related potentials and the lateralization of the motor cortex, it was decided to investigate further any differences found in these potentials in relation to the foot prepared to be moved and the amplitude recorded over either hemisphere.
Materials and methods

Participants

After informed consent was obtained, 22 healthy, right-handed male study participants were randomly assigned to their group. Twelve participants aged between 20 and 47 (mean 28.58) years prepared to carry out the movement and executed it while the other 10 participants aged between 21 and 47 (mean 29.3) years prepared to carry out the same movement but did not execute it.

Materials

Stimuli were 2000 Hz tones of 20 ms duration (2 ms rising, 16 ms plateau, and 2 ms fall) and 80 dB sound pressure level. These sounds were presented by means of a computer and headphones at a rate of one every 3000 ms. An adjacent computer was employed to record and analyse the psychophysiological activity. Using this system, the brain electrical activity was recorded through an electrocap while simple cup electrodes of 1 cm diameter were necessary for the electrooculogram (EOG) and electromyogram (EMG).

Procedure

Four blocks of the previously described stimuli were presented binurally. The first two blocks had 100 identical stimuli and lasted for 5 min. Both blocks were administered with the purpose of allowing participants to practice the task. The last two blocks, in which the electrical activity was recorded, had 200 stimuli and lasted for 10 min. A break of 5 min was given after each block to avoid fatigue and habituation. The instructions given to participants were to get ready to flex and extend their toes abruptly before they heard each tone, but only one of the groups had to respond to the stimulus by executing the movement.

While participants were seated, with their eyes opened and conducting the task, the movement-related brain potentials were recorded using 20 active electrodes (Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, Oz, O2). N1, over the tip of the nose, acted as the reference and Fpz was the ground electrode. The EOG and EMG were recorded bipolarly. For the vertical EOG, two electrodes were placed, one above and one below the right eye, and for the horizontal EOG, an electrode was placed at each side of the external canthus of both eyes. For the left and right EMG, two similar electrodes were placed 3 cm apart over the ‘flexor digitorum longus’ of either lower limb.

Electrical activity recorded through all channels was amplified by a gain of 20000 and sampled at a rate of 500 points/s during the 2000 ms before and the 1000 ms after the stimulus was presented. Impedance was kept below 10 KΩ. In the case of brain and ocular activity, a 0.05–40 Hz band pass filter was used. This filter was changed from 10 to 100 Hz for the EMG.

Once the electrical activity was recorded, the resulting epochs were averaged as a means of increasing the signal-to-noise ratio. A maximum of 200 epochs per block could be included in this computation. If the influence of the EOG over the electroencephalogram (EEG) was greater than 100 μV, or if there was no difference between the EMG and the baseline when a muscular contraction should have happened, or if there was divergence when the motor act should not have taken place, then the epoch in question was rejected. In order to use the same averaging procedure for both groups, averages were time-locked to the stimulus.

Using this method, four movement-related brain potentials were recorded and analysed. The readiness potential was the gradually increasing negative trend that started around 1700 ms before the auditory stimulus [1] and was measured from −200 to 0 ms. A small voltage difference with a maximum value in the range of 0–100 ms was the premotion positivity. The motor potential followed in the range of 100–150 ms [7] and finally the reafferent potential was measured between 150 and 250 ms. The peak-to-peak amplitude was measured with respect to the previous peak for each one of these potentials.

The four factors in this study were foot (left and right), electrode position (frontal, central, parietal and occipital), laterality (left hemisphere, midline and right hemisphere) and group (movement vs. non-movement). The dependent variable was the amplitude of each one of the movement-related brain potentials measured and data were analysed using multivariate analysis of variance (MANOVA).

Results

The grand mean waveforms obtained for both groups when they were conducting the task with each foot can be seen in Fig. 1. As shown in the figure, the group that only prepared to execute the movement revealed a lower readiness potential amplitude (mean −3.32 μV) than the group that not only prepared to flex their toes but also flexed them (mean −9.26 μV), F(1,20)=29.84, P=0.001. This and other MANOVA results can be found in Table 1.

Also, a significant interaction was observed between electrode position and group [F(3,18)=7.18, P=0.002]. Amplitude values corresponding to frontal and central positions varied as a function of whether the movement was carried out [F(1,20)=22.35, P=0.001], and the same happened in central and parietal levels [F(1,20)=6.93, P=0.016], and in parietal and occipital levels [F(1,20)=9.54, P=0.006]. Specifically, in the movement group, the readiness potential amplitude recorded from the parietal position was similar to that obtained from the central position (mean difference=−0.86, P=0.124). In the no-movement group, the amplitude recorded from the parietal position was greater than that obtained from the central position (mean difference=−0.88, P=0.041).

The interaction laterality × group was significant too [F(2,19)=13.85, P=0.001]. The increase in readiness potential amplitude reached in the midline in relation to the left hemisphere was greater in the movement group than in the no-movement group [F(1,20)=11.31, P=0.003]. Similarly, the increase in amplitude observed in the midline in relation to the right hemisphere was also greater in the movement group than in the no-movement group [F(1,20)=28.89, P=0.001].

In addition, readiness potential amplitude values obtained from the different position levels not only depended on the specific laterality level but also on whether the movement was executed [F(6,15)=3.50, P=0.023]. The increase in amplitude reached over Cz in comparison with C3 was greater in the movement group than in the no-movement group [F(1,20)=14.46, P=0.001] as happened between Cz and C4 [F(1,20)=24.97, P=0.001].

No group differences were found in the premotion positivity. The interaction position × group, however, proved to be significant in the motor potential [F(3,18)=4.09, P=0.022], in which an increase was observed from the
frontal to the central position in the movement group in contrast to what happened in the no-movement group [F(1,20)=5.34, P=0.032]. No differences were found between both groups with respect to central and parietal levels [F(1,20)=1.70, P=0.206], nor between parietal and occipital levels [F(1,20)=3.99, P=0.059].

The amplitude of the motor potential obtained across the levels of laterality not only depended on the foot involved in the task but also on whether the movement was carried out [F(2,19)=3.82, P=0.040]. When the task involved the right foot and was carried out by the movement group, no interhemispheric differences were found (mean difference=0.47, P=0.144). In a similar condition in the no-movement group, however, the amplitude was greater over the contralateral hemisphere than over the ipsilateral hemisphere (mean difference=0.33, P=0.039). In contrast, when the foot involved in the task was the left foot and the movement group was carrying out the task, the amplitude reached over the ipsilateral hemisphere was greater than that reached over the contralateral hemisphere (mean difference=1.28, P=0.001). No interhemispheric differences were observed when the no-movement group executed the task with the left foot (mean difference=0.46, P=0.198).

In addition, the motor potential amplitude values obtained across the different position levels not only depended on the level of laterality but also on the foot concerned [F(6,15)=2.99, P=0.040]. No significant interhemispheric differences were found in any electrode position when the foot concerned was the right foot. In the case of the left foot, however, the amplitude was greater over the left hemisphere than over the right hemisphere in the frontal position (mean difference=0.57, P=0.024), central position (mean difference=1.47, P=0.001) and parietal position (mean difference=1.02, P=0.001). In the occipital position, the mean values recorded were not of a negative sign but there were also differences between both hemispheres (mean difference=0.58, P=0.024).

The reafferent potential amplitude values recorded across the different levels of laterality depended on the foot involved in the task as well as on whether the movement was executed [F(2,19)=7.47, P=0.004]. In the movement group, no significant differences were found between the values attained over both hemispheres when the activity recorded under both feet conditions was compared [F(1,11)=3.86, P=0.075], nor were there any differences between the left hemisphere and the midline [F(1,11)=0.03, P=0.847]. The amplitude increase recorded over the midline in comparison with the right hemisphere, when the foot involved in the task was the right foot, however, contrasted significantly with the decrease observed in the case of the left foot [F(1,11)=31.61, P=0.001]. In addition, there were no significant differences when making pairwise comparisons between the amplitudes recorded from the three levels of laterality in the movement group, both when the task was executed with the right foot as well as when it was executed with the left foot.

In the no-movement group, no significant differences were found between the levels attained over both hemispheres when the activity recorded under both feet conditions was examined [F(1,9)=0.75, P=0.409]; neither were there any differences over the midline in comparison with the left hemisphere [F(1,9)=0.18, P=0.676] or right hemisphere [F(1,9)=1.53, P=0.247]. The amplitude was greater over the midline than over the left hemisphere (mean difference=0.61, P=0.004) or the right hemisphere (mean difference=0.57, P=0.012), however, when making pairwise comparisons between the three levels of laterality when the foot involved in the task was the right foot. The same pattern of results were seen in the case of the left foot: mean difference=0.66, P=0.010 and mean difference=0.84, P=0.014, respectively.

### Discussion

Results from this study demonstrate that the level of preparation to carry out a motor act in a repetitive task is greater when the motor act is to be executed than when it is to be cancelled. Topographic differences between these two conditions are also observed. The readiness potential amplitude is maximum over central positions, close to the motor cortex, when the movement is carried out, whereas in the group that does not execute the movement, the potential difference measured in a period in which the negativity preceding the stimulus also intervenes [12] is of greater amplitude in parietal positions. Although the possible role played by the somatosensory cortex in designing a plan that allows for the necessary mental preparation to carry out the movement while knowing that the muscles must remain in a relaxed state after the temporal marker cannot be

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**Table 1 Multivariate analysis of variance results for each movement-related brain potential**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Readiness potential</th>
<th>Premotion positivity</th>
<th>Motor potential</th>
<th>Reafferent potential</th>
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<tr>
<td></td>
<td>F</td>
<td>df</td>
<td>P</td>
<td>F</td>
</tr>
<tr>
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<td>0.00</td>
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<td>0.937</td>
<td>0.15</td>
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<td>Position</td>
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<td>40.82</td>
<td>0.001</td>
<td>8.34</td>
</tr>
<tr>
<td>Position × group</td>
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<td>7.18</td>
<td>0.002</td>
<td>0.19</td>
</tr>
<tr>
<td>Laterality</td>
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<td>26.91</td>
<td>0.001</td>
<td>8.67</td>
</tr>
<tr>
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<td>13.85</td>
<td>0.001</td>
<td>1.99</td>
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<tr>
<td>Foot</td>
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<td>1.03</td>
<td>0.400</td>
<td>0.58</td>
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<tr>
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<td>0.002</td>
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<tr>
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<td>0.023</td>
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<td>1.01</td>
<td>0.452</td>
<td>0.64</td>
</tr>
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</table>

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underestimated, this topography is most likely because of the fact that it is in the parietal electrodes where the stimulus preceding negativity presents its greatest amplitude [6].

The electrical activity recorded over each hemisphere and the midline is not dependent on the foot prepared for action. This symmetrical distribution of the readiness potential is similar to the finding of Shibasaki and collaborators [13], who did not find any side difference with regard to the readiness potential in feet movements. Brunia and Vingerhoets [14] did not find significant differences either, when homologous electrode positions (C3 and C4, C’3 and C’4) were compared. These results suggest that some precise conditions need to be met in order to observe a specific level of lateralization including whether the limb prepared to be moved is an upper or lower limb, the position of the electrodes in relation to the neural generators, and perhaps even the way in which the epochs are synchronized.

The fact that this work concerns foot movements and not hand movements is also worth emphasizing. Relatively little work has been done on foot movement [11], but the readiness potential on foot movements is of the essence as it allows the studying, for instance, of patients with spinal cord injuries at lower segments.

![Grand mean waveforms for both movement and no-movement groups.](image)

**Fig. 1** Grand mean waveforms for both movement and no-movement groups.
The presence of the premotion positivity [15] is confirmed in the current study. No effects related to the foot involved in the task or differences between both groups are found in this potential, which coincides with previous literature [16] and suggests that this wave could be just a transition between the readiness potential and the motor potential without much intrinsic value. This interpretation is backed by the inability to identify the premotion positivity in subcortical recordings [17].

The activity recorded in the motor potential interval is not significantly different between the group that carries out the movement and the group that cancels the motor act. In spite of this statistical similarity, the source and meaning of this activity is thought to be quite different between both conditions. In the no-movement group, the polarity change is speculated to be due fundamentally to the abrupt oscillation (N1) produced by the stimulus, whereas in the movement group it is reasonable to think that the activity is composed not just by N1 but also by the motor potential [11]. This interpretation is supported by the task characteristics, the EMG findings that are in line with the instructions and the amplitude recorded from various EEG electrodes. For instance, the amplitude difference recorded from the central position in comparison with the frontal position is greater and of opposite sign in the group that carries out the movement than in the group that receives the stimulus but does not execute the action. When participants execute the action, the amplitude is maximum in central positions close to the primary motor cortex. In addition, the activity recorded over both hemispheres and the midline when the task is conducted with either foot is more homogenous in the no-movement group than in the movement group. In other studies in which participants were asked to imagine the movement [18,19], the motor cortex was also activated, but to a lesser degree than when the movement had to be executed.

With regard to the last potential analysed in this study, the reafferent potential, previous results show that it occurs after active as well as after passive movements [8,20]. The study reported here indicates that a wave similar to the reafferent potential also occurs when participants prepare to carry out the movement but later cancel the order. The influence that the stimulus has over this last potential is an area that requires further investigation in order to establish any possible differences or similarities that may exist, for example between P300 and the reafferent potential. So far it is speculated to be due fundamentally to the abrupt oscillation (N1) produced by the stimulus, whereas in the reafferent potential also occurs when participants prepare to carry out a specific movement and conduct it is significantly greater and of opposite sign in the group that carries out the movement in comparison with the group that does not.

**Conclusion**

The degree of mental preparation exercised by people who prepare to carry out a specific movement and conduct it is significantly greater than the level shown by participants who get ready to carry out the same movement but do not execute it. The fact that there were no group differences for the amplitude of the premotion positivity, motor potential and reafferent potential suggests that once a movement is prepared, the magnitude of these potentials does not depend on whether the motor act is carried out.

**References**