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Imitating versus non-imitating movements: Differences in frontal electroencephalographic oscillatory activity

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Abstract

Non phase-locked oscillatory changes were studied in seven healthy volunteers during two different reaction time movement paradigms, in which the stimulus was a wrist movement (either extension or flexion) performed by another person seated in front of the subject (examiner). In the first paradigm (imitation), the subject was instructed to perform the same movement observed. In the second paradigm (non-imitation), the subject was instructed to perform the opposite movement (flexion when an extension was observed, and vice-versa). Changes in the 7–37 Hz range band were determined by means of Gabor transforms. A frontal energy increase (event-related synchronization, ERS) around 15 Hz could be observed in the frontal region after the examiner's movement; this frontal ERS was significantly larger in the non-imitation paradigm. A typical alpha and beta movement-related event-related desynchronization/synchronization (ERD/ERS) pattern was also observed in both paradigms in the central region. The beta-ERD was significantly larger in the imitation paradigm. Our results show that the motor preparation mechanisms involved in an imitated and a non-imitated movement are different.

Keywords: Event-related desynchronization; Event-related synchronization; Mirror movements; EEG; Wrist

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Cortical oscillatory activity may play a significant role in sensory, motor and cognitive binding mechanisms [10,20,24]. Self-initiated movements are accompanied by a definite pattern of changes in cortical oscillatory activity. In the beta frequency range (15–30 Hz), this pattern consists of a decrease (beta event-related desynchronization, ERD) that begins at least 1.5 s before the beginning of the movement, followed by an increase (beta event-related synchronization, ERS) that peaks 0.5–1 s after the end of the movement [25]. In the alpha band (8–12 Hz), the ERD lasts longer, and the post-movement ERS is much lower [26]. Stimulus-induced movements show a similar pattern of oscillatory changes, although the ERD only begins after the stimulus unless it is rhythmic and therefore predictable [1]. A recent study in go/no-go paradigms found a frontal synchronization, peaking around 15 Hz and 450 ms after the decisory stimulus, coincident with the movement-related beta-ERD [2]. This frontal ERS was proposed to be related to decision processes.

In the monkey cerebral cortex area F5 (inferior frontal area), there are neurons (named "mirror" neurons) that discharge not only when a movement is executed, but also when a movement is observed [11,22]. Nishitani and Hari compared phase-locked MEG responses related to spontaneous movements, imitation movements and movement observation without action in a group of healthy volunteers [17]. They found activation of the left inferior frontal cortex (area 44) in the three conditions, but higher during imitation. Together with the results of previous PET studies [9,12,23], their finding suggests that this area, cytoarchitectonically similar to the F5 area in the monkey, is the human equivalent of the "mirror system". Further studies have shown that the imitation of a movement also activates this human mirror system [13].

On the other hand, the observation of a movement is accompanied by an alpha and beta-ERD over motor areas, similar to the movement-related ERD [5,8]. This ERD has also been related to the mirror system [16,18,21].

Our hypothesis is that an imitative and reactive strategy is used for the realisation of more automatic or less "voluntary" movements, while for the more "voluntary" movements it is necessary to inhibit this normal imitative tendency. This

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could explain the "imitation and utilisation" behaviour usually observed in frontal lesions.

The aim of our study was to test this hypothesis, studying the differences in electroenephalographic oscillatory changes between the imitation of movements observed and the performance of the same movements while observing different ones.

We studied changes in oscillatory activity in the 7–37 Hz range in seven healthy subjects (age 22–35, three female) in two different choice reaction time movement paradigms, in which the stimulus was a wrist movement (either extension or flexion) performed by another person seated in front of the subject (examiner). The movements were performed in a random sequence, with random interstimulus interval ranging from 7 to 12 s. In the first paradigm (imitation), the subject was instructed to perform the same movement observed. In the second paradigm (non-imitation), the subject was instructed to perform the opposite movement (flexion when an extension was observed, and vice-versa). All the subjects gave their written consent after a detailed explanation of the procedure, previously approved by the Institutional Ethics Committee. Both paradigms were studied during the same session, in alternate blocks of 10 min. Twenty-one channels of EEG (10–20 system) referred to linked earlobes were recorded using a commercial EEG cap (Electrocap Inc.). The signal was amplified and digitized at 200 Hz using Stellate Harmonie software and LaMont amplifiers. A reference-free montage was obtained after the recording by means of the intrinsecal Hjörth laplacian.

The data were segmented into 6.5 s sweeps centered around the examiner's surface EMG signal (flexor carpi and extensor carpi), used as level trigger. The segmentation was carried out separately for each block. The individual sweeps were manually reviewed offline before any further analysis, excluding those with visible artifacts (usually muscle artifact) or wrong performance (assessed by the EMG pattern).

A preliminary analysis was carried out comparing flexion and extension movements in each paradigm. No significant differences were observed in the reaction time nor in the average of the time–frequency plots (see below) between flexion and extension within each condition, so both flexions and extensions were included in the statistical comparison between imitated and non-imitated movements.

An alternative offline realigning of the sweeps was also performed, using the subject's EMG as trigger instead of the examiner's EMG. All the analysis procedure described below was performed both using the original sweeps (triggered by the examiner's EMG) and the realigned sweeps (triggered by the subject's EMG).

A time–frequency (Gabor) energy distribution was calculated for every single trial (in the 7–37 Hz range) and averaged afterwards, in order to add all oscillatory activity, phase-locked and non phase-locked to the trigger of the sweeps. The average of the transforms from each paradigm was divided by the mean energy for each frequency during a 1-s baseline period (from 3.25 to 2.25 s before the observer's movement), and displayed in a 3D normalized coloured graph. In order to avoid discontinuity effects, only the five central seconds were displayed. The energy changes in the most representative frequencies for each band were also displayed linearly for clarity.

Two different statistical approaches were used. A non-parametric test (paired Wilcoxon signed rank test) was used for statistical comparison in both cases, as neither energy values nor percentual changes have a gaussian distribution. In the first approach, each time–frequency plot was divided into 400 small windows (20×20) for the comparison. Absolute energy values (before normalisation) were averaged for each window. The Wilcoxon signed rank test was used to compare in each window the imitation and the non-imitation paradigms, pairing sequentially sweeps from the same subject and movement (extension or flexion). To avoid the effect caused by multiple comparisons, a Bonferroni correction was applied to the p values. A conservative approach is to consider the 400 comparisons made per plot; then a 99% confidence interval corresponds to a p value of 0.000025 (values of 4.6 and -4.6 in the colour plot). This mathematical procedure (TF energy distribution estimation, averaging, normalization, and statistical comparison) was applied to each individual subject and to each group as a whole. In the second approach, the minimum or maximum values of energy changes observed in each significant region (alpha and beta-ERD, frontal ERS; see below) were individually measured (four measures per subject, flexion and extension, imitation and non-imitation) and compared between imitation and non-imitation conditions using again a paired Wilcoxon signed rank test.

Reaction times, measured as the interval between the beginning of the observer's movement and the beginning of the examined subject's movement, were significantly longer in the non-imitation paradigm (mean values 472 ± 131 versus 533 ± 178 ms, $p < 0.001$ in a non-matched samples t-test). A beta-ERD that began after the stimulus (observer's movement) was present over the contralateral central region in both paradigms (Fig. 1). The beta-ERD became bilateral during the movement, and was followed by an ERS, also predominant over the contralateral central region. The amplitude of the ERD was significantly larger in the imitation condition (both in the single-sweep comparison – see Fig. 2, left – and in the minimum values comparison, $p = 0.038$). This difference could be observed both when the sweeps were segmented using the observer's EMG and when the sweeps were segmented using the subject's EMG. An alpha-ERD beginning after the observed movement was also found, with similar topography (Fig. 2, right). As opposed to the beta-ERD, no significant differences were present between both paradigms.

A limited ERS around 15 Hz, which began after the stimulus (examiner's movement), could be observed in the frontal region (maximal value at Fz; see Fig. 3, bottom), simultaneously with the central ERD. This frontal ERS was significantly larger in the non-imitation paradigm (both in the single-sweep comparison and in the maximum values comparison, $p = 0.035$ in the latter). The peak latency was longer in the non-imitation paradigm when the sweeps were aligned with the observer's movement (0.55 versus 0.73 s after the trigger; $p = 0.03$ in a Wilcoxon signed rank test comparing individual peak latency values), but not when the subject's EMG was used for realign-