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ORIGINAL ARTICLE

Assessment of the haptic robot as a new tool for the study of the neural control of reaching

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Abstract Current experimental methods for the study of reaching in the MRI environment do not exactly mimic actual reaching, due to constrains in movement which are imposed by the MRI machine itself. We tested a haptic robot (HR) as such a tool. Positive results would also be promising for combined use of fMRI and EEG to study reaching. Twenty right-handed subjects performed reaching tasks with their right hand with and without the HR. Reaction time, movement time (MT), accuracy, event-related potentials (ERPs) and event-related desynchronisation/synchronisation (ERD/ERS) were studied. Reaction times and accuracies did not differ significantly between the two tasks, while the MT was significantly longer in HR reaching (959 vs. 447 ms). We identified two positive and two negative ERP peaks across all leads in both tasks. The latencies of the P1 and N2 peaks were significantly longer in HR reaching, while there were no significant differences in the P3 and N4 latencies. ERD/ERS topographies were similar between tasks and similar to other reaching studies. Main difference was in ERS rebound which was observed only in actual reaching. Probable reason was significantly larger MT. We found that reaching with the HR engages similar neural structures as in actual reaching. Although there are some constrains, its use may be superior to other techniques used for reaching studies in the MRI environment, where freedom of movement is limited.

Keywords Reaching · Haptic robot · Event-related potentials · Event-related synchronisation/desynchronisation · Functional magnetic resonance

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Introduction

Reaching involves translating visual and proprioceptive information into a motor plan and action [1–3]. Experiments in animals [2, 4, 5], functional neuroimaging and electrophysiological studies in humans [6–8] have shown involvement of a widespread fronto-parietal network in its control. The posterior parietal cortex integrates spatial coordinates of the target with proprioceptive (arm position) information, while the frontal motor areas predominantly contribute to the planning, execution and inhibition of reaching movement [9, 10]. The knowledge of extent of these dedicated regions, their location and the manner in which information is processed in humans is far from complete.

Available methods for human studies either lack spatial (electrophysiological (EEG) methods), temporal (imaging methods) resolution or they are invasive [10]. The combination can yield more meaningful results. Experimental paradigms used for testing human reaching by these methods are quite dissimilar. The differences are mainly due to the limitations imposed by the MRI environment, where the freedom to move is largely reduced. In such investigations, reaching was typically only imitated by, for example, finger extension/finger pointing [11–13] or by moving a joystick handle [14]. Consequently, movements were limited to the distal part of the arm and mostly exerted in two-dimensional space. Due to technical limitations, the trajectories and accuracy of reaching in such studies could not be properly determined.

By measuring and dynamically simulating arm and hand movements, a haptic robot (HR) can be a useful tool for motor control paradigms [15]. The HR is a human computer interface, where the user acts as a force source and the HR actively provides proprioceptive and force feedback, as well as continuously recording arm position. The HR has three degrees of freedom and fulfils the general requirements for the MRI setting. In addition, we have shown [16] that the HR can be used in an MRI scanner, which in combination with EEG provides an opportunity for the simultaneous use of these research tools.

However, before the HR can be used in reaching studies, it is important to clarify how the brain processes of motor programming in this situation correlate to those performed during actual reaching. We compared actual and HR reaching by studying behavioural parameters, event-related potentials (ERPs) and event-related desynchronisation/synchronisation (ERD/ERS) evoked by reaching.

Materials and methods

Subjects

Twenty healthy subjects, right-handed, with normal vision (mean age 28.8) were divided in two groups of 10. The time interval between consecutive reaching (0.5 and 1.5 s) used in the first group was too short to allow for the ERD/ERS analysis. We therefore examined another group volunteers in which the interval between the repeated reaching ranged from 6 to 7 s. The National Ethics Committee approved the experimental procedures design and all subjects gave written informed consent prior to the procedure.

Tasks

Every subject performed two similar tasks, actual (non-instrumental) and HR (instrumental) reaching (Fig. 1). In both tasks, subjects sat in a darkened room facing touch screen. White square target (2 × 2 cm) appeared in right upper quadrant and remained in position for 1 s. Randomised target positions were used in an attempt to avoid habituation and anticipation effects. At the start of the experiment, subjects were required to complete a training session of 30 trials of the actual reaching task and 50 trials of the HR reaching task.

In the actual reaching task, subjects were instructed to reach from the mouse for the target with their right index finger as fast and as accurately as possible. We programmed task in E-Prime version 2.0 (Psychology Software Tools, Inc., Pittsburgh, USA).

The virtual environment for implementing HR reaching was programmed by one of the authors [16]. Their right index finger was attached to the arm of the three degree of freedom rotational joint of the Phantom. Subjects were instructed to hit the target with the cursor as fast and as accurately as possible (Fig. 1).

Every subject performed each task 200 times. Reaction time (RT) was measured from target presentation to the

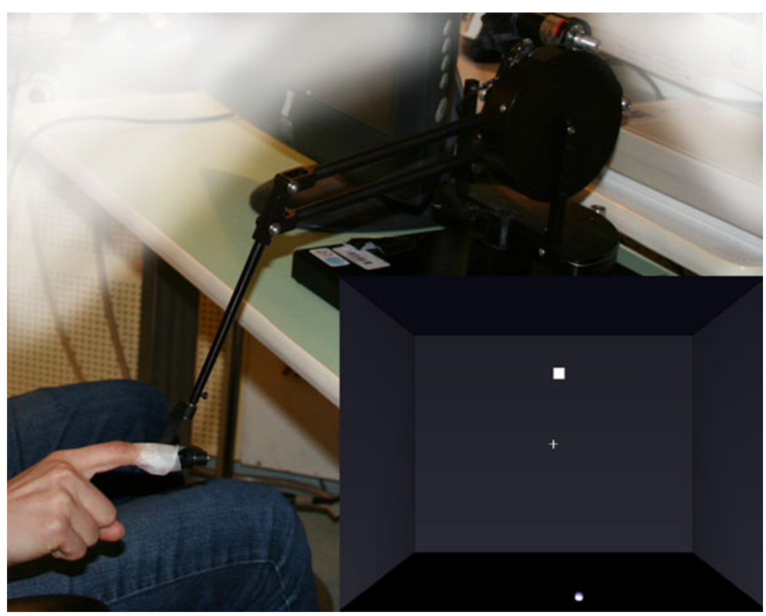


Fig. 1 The Phantom Premium 1.5 haptic robot with the virtual room. Its dimensions are 140 mm × 100 mm × 80 mm. *White square* is the target, *white ball* the cursor, and the *cross* in the centre the point of fixation

Table 1 The reaction and movement times (mean values and standard deviations) of the actual and haptic robot reaching in the two groups of volunteers

	Group 1	Group 2
Reaction time (ms)		
Actual reaching	350/41	331/39
HD reaching	351/41	401/50*
Movement time (ms)		
Actual reaching	455/124	447/139
HD reaching	611/223*	959/363*
Error		
Actual reaching (mm)	10/3	2/1
HD reaching (mm)	12/18	8/4*

Values are mean/SD. Movement times differed significantly between the tasks (* paired t test, $p < 0.05$) while the reaction time differed only in the second group of volunteers

Table 2 Mean values/standard deviations of latencies and amplitudes of individual peaks of the event-related potentials obtained in the central leads

Lead	Peak	Latencies (ms)		Amplitudes (µV)	
		Reaching	HR reaching	Reaching	HR reaching
Fz	N1	141/23	173*/11	2.1/1.89	2.1/2.09
Cz	P1	130/26	146*/26	−3.5/3.0	−1.0/3.7
Pz	P1	139/20	166*/15	−2.0/3.3	−2.4/3.4
Oz	P1	160/18	177*/12	−1.1/1.8	−1.8/1.3
Fz	P2	210/33	228*/7	−1.4/1.2	−1.5/1.4
Cz	N2	212/36	218*/14	1.7/1.3	0.6/0.6
Pz	N2	214/13	229*/12	1.1/1.9	2.11/2.2
Oz	N2	226/23	250*/33	1.4/5.0	2.5/1.6
Fz	N3	336/41	354/29	−1.7/3.0	−3.8/2.3
Cz	P3	389/26	338/29	1.7/2.6	0.1/2.5
Pz	P3	360/34	348/21	8.4/11.8	3.0/3.3
Oz	P3	359/93	350/40	5.6/2.8	5.2/2.9
Fz	N4	651/90	686/71	5.5/2.6	4.7/1.3
Cz	N4	609/62	593/88	−1.3/2.2	−0.3/1.1
Pz	N4	632/112	617/95	−2.6/2.5	−1.2/2.0
Oz	N4	561/150	577/59	0.6/2.4	−0.1/2.1

* Statistically significantly longer latencies of the event-related potentials for reaching with haptic robot (HR) compared to the actual reaching (paired t test, $p < 0.05$). No differences in the amplitudes were detected between the tasks

releasing of the mouse button or the robot hand from the zero position. The movement time (MT) was calculated from the time of releasing the mouse button to the time of touching the screen or when the robot hand was released to the time when the ball cursor hit the target. The accuracy of reaching was calculated as the distance between the target centre and the site of contact of the pointing finger with the touch screen or of the cursor with the back wall of the virtual room.

Data acquisition and processing

The electroencephalogram (EEG) was recorded using 64 scalp Ag/AgCl electrodes (BrainCap64, Brain Products GmbH, Germany) placed according to the 10–10 system [17]. The FCz electrode was used as reference and the AFz electrode as ground. Before results evaluation, the average reference electrode was calculated from 61 electrodes (all except EOG1, EOG2 and ECG). EEG signals were amplified and filtered with a bandpass filter of 0.1–250 Hz by means of the BrainVision Recorder system (Brain Products GmbH, Germany) and sampled at 500 Hz. The time of appearance of the visual stimulus (target) was presented as trigger generated by the software.

EEGs of each subject were analysed offline. Eye-blink artefacts were first removed by the ICA algorithm. The EEG was then segmented into 2,000 ms epochs (1,000 ms before and 1,000 ms after target presentation). Such epochs were then analysed visually and those with artefacts were rejected before averaging. Responses of individual subjects in first group of volunteers were averaged initially to obtain event-related potentials (ERPs). Grand averages of ERPs were then calculated for both tasks. For the ERD/ERS evaluation, experiments were repeated with longer inter-trial intervals (second group). EEG from the electrodes F1, Fz, F2, C3, Cz, C4, P1, Pz, P2, O1, Oz, and O2 was segmented into 6,000 ms epochs (3,000 ms before and 3,000 ms after target presentation). Each EEG segment was bandpass filtered from 5 to 35 Hz (frequency resolution 1 Hz). Filtering was performed with phase-correction algorithm to prevent additional delays introduced by the filter. The next step was subtraction of the mean voltage value of individual segments from the raw signals and squaring. Finally, the average of all trials was calculated. ERD/ERS was expressed as a proportion of power increase or decrease in regard to the mean power of the whole interval.

Table 3 Mean/standard deviations of the event-related potential delays in the central leads between the actual and haptic robot (HR) reaching attained by cross correlation in four different time intervals

Lead	Time intervals (ms)			
	80–350	80–215	215–350	351–620
Fz (ms)	6/15	−7/22	2/26	6/14
Cz (ms)	5/14	4/7	9/17	−16/68
Pz (ms)	0/3	4/6	2/4	12/23
Oz (ms)	−1/21	−4/33	−8/41	−8/59

Data analysis

Behavioural data

For each subject, we calculated the average and standard deviation of the RT, MT, and accuracy for actual and instrumental reaching. We compared differences between the tasks with paired *t* test (SPSS 13.0).

Event-related potentials (ERP)

The waveforms derived from electrodes overlying fronto-parietal-occipital network involved in reaching were analysed in more detail (Fig. 2). ERP components were named according to their polarity (*P* positive, *N* negative) and their order of appearance.

Individual mean values of the latencies and amplitudes of these components were calculated at each of the electrode positions for both tasks. We compared differences between tasks with paired *t* test.

Fig. 3 Grand averages of the alpha (8–13 Hz) event-related synchronisations and desynchronisations in the C3 derivation (*left*) and their scalp topographies related to the actual (**a**) and haptic robot (**b**) reaching (*right*). Topographies refer to the three 100 ms time intervals denoted by *vertical lines* and numbered from 1 to 3 (*left*). ERDs appeared before target onset. After that they were maximal in the central and parietal electrodes contra-lateral to the reaching arm. At their peaks, ERDs were symmetrical and widely distributed over the occipital, parietal and frontal cortices. ERS rebound appeared only in the actual reaching ▶

Latency differences of ERPs between both tasks were also analysed by cross correlating these signals. The delays were determined by measuring the time interval between signals at which maximal correlation was obtained in two time segments. The first segment covered the time interval from 80 to 350 ms after target onset (roughly between the arrival of the visual stimulus at the cortex and movement onset). Cross correlations were obtained separately for its early (80–215 ms) and late (215–350 ms) components. These intervals were chosen because latencies of the first two ERP peaks, which differed significantly between the studied

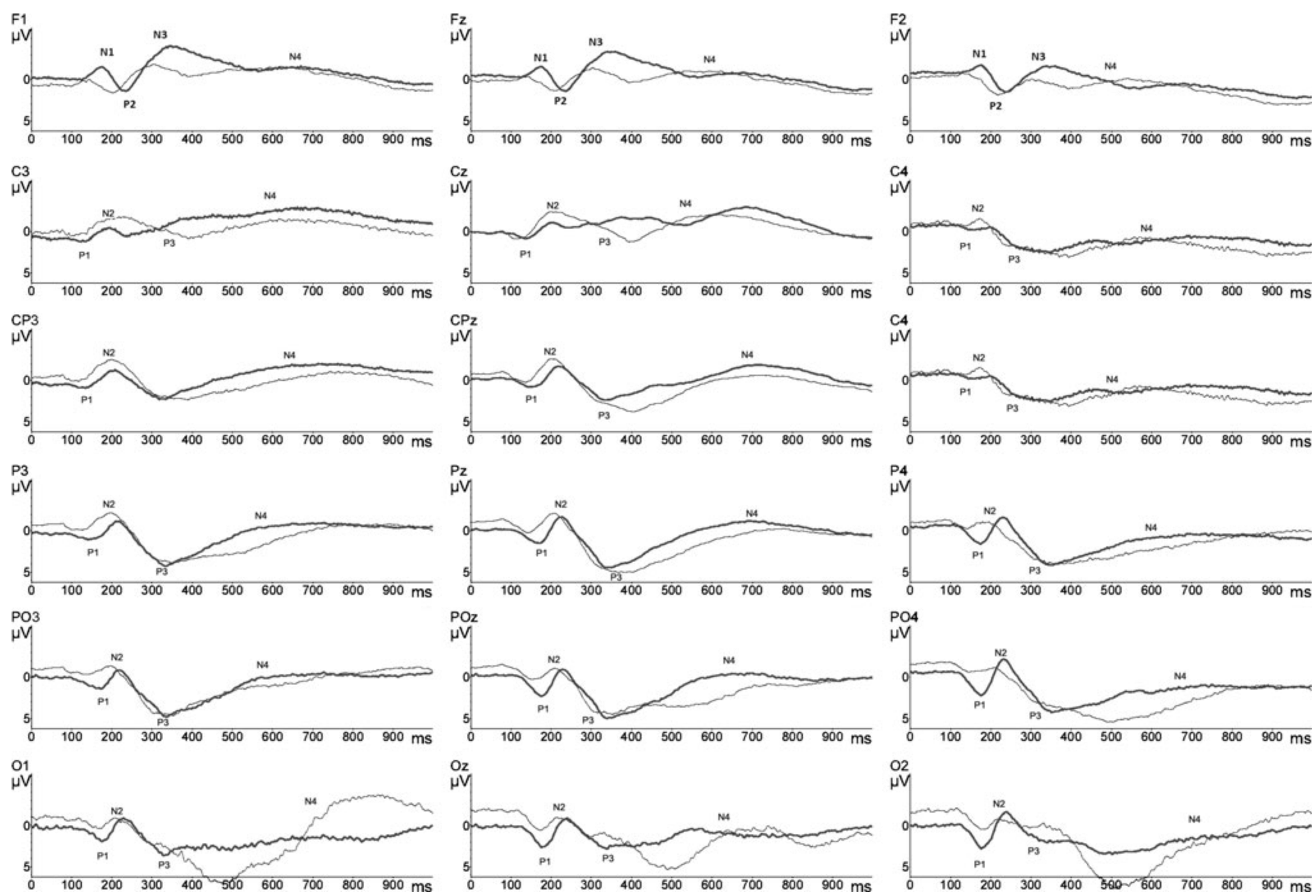
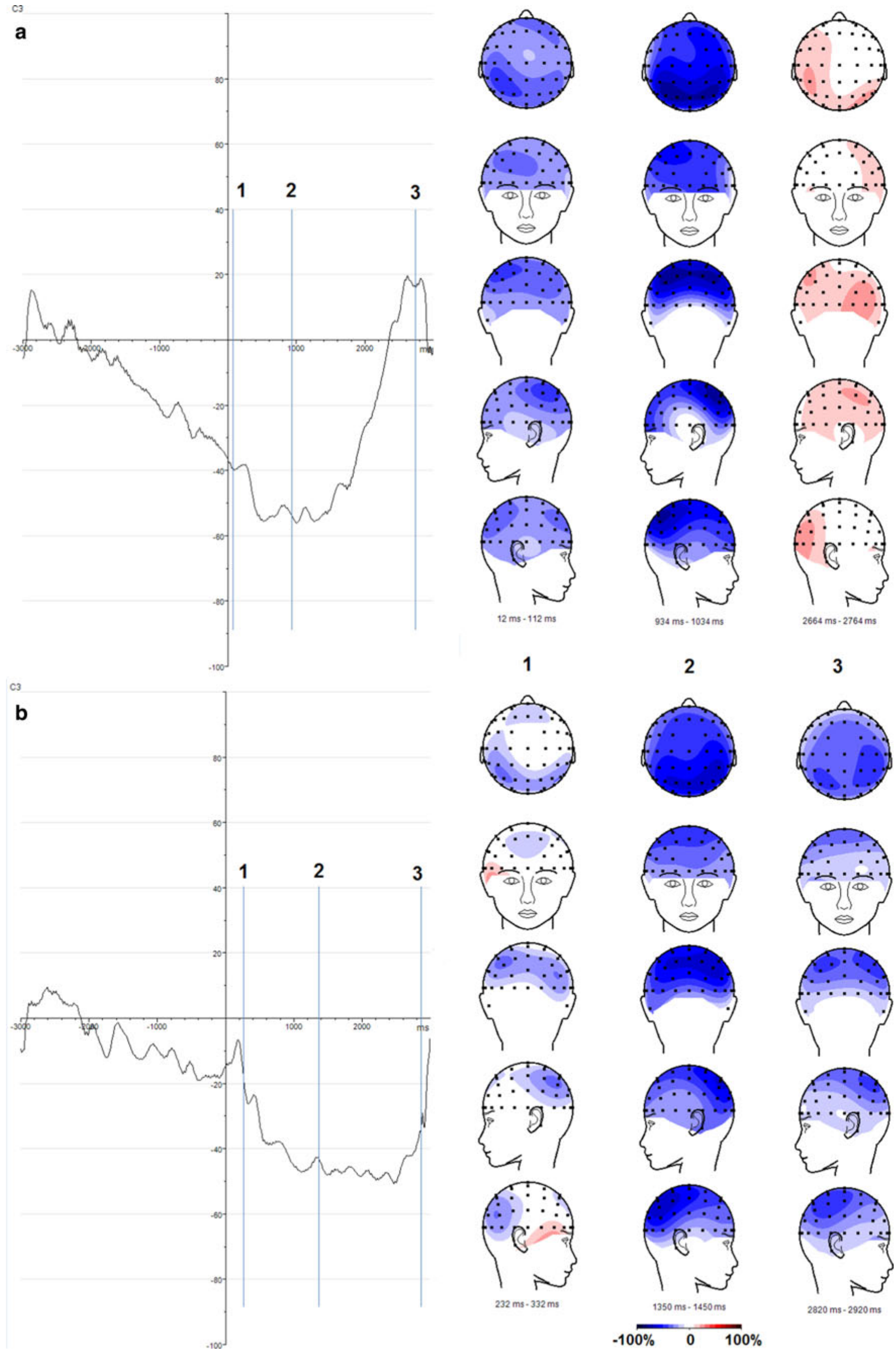
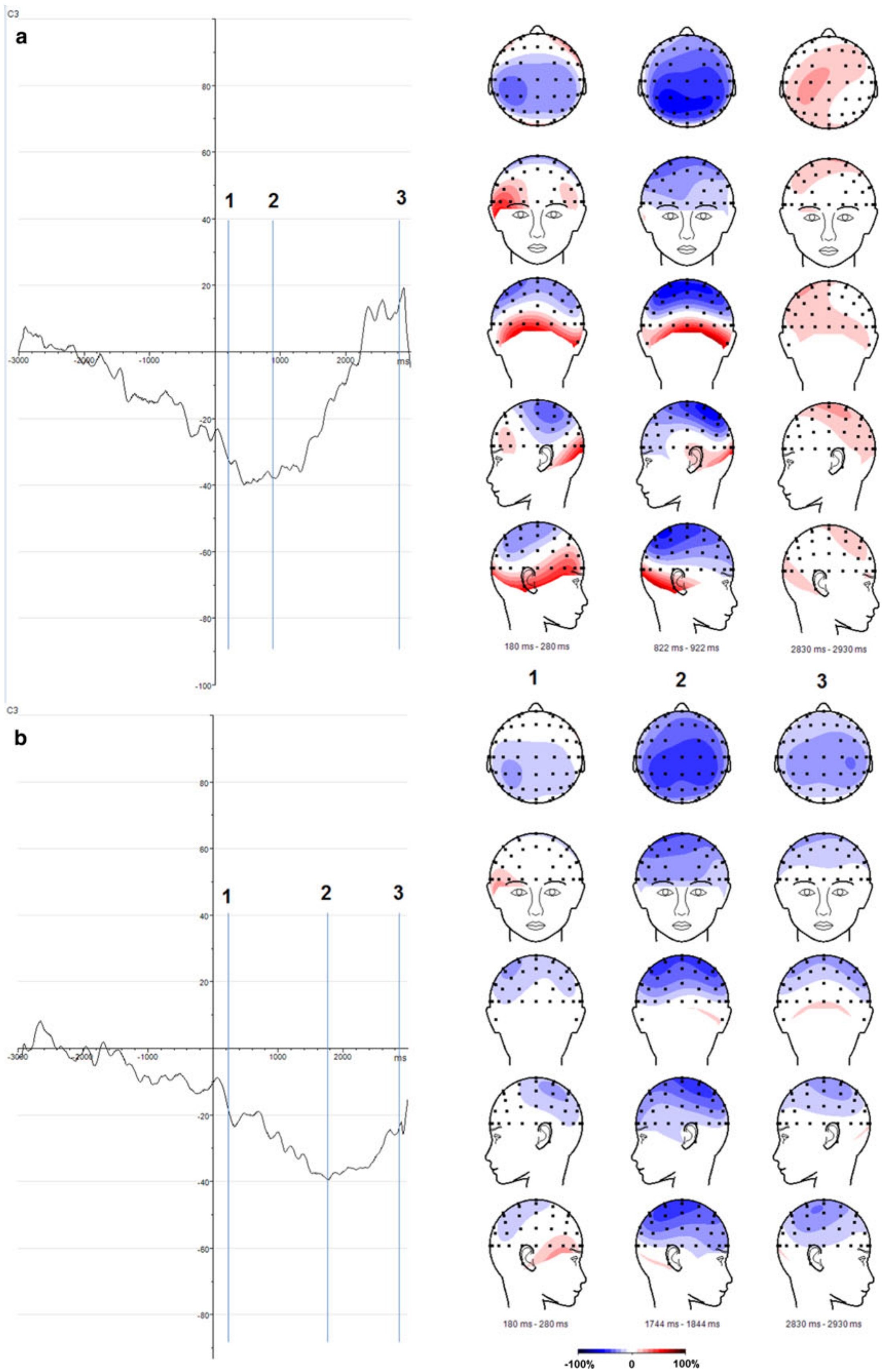


Fig. 2 Grand averages of event-related potentials (*thin black curves* reaching, *bold black curves* reaching with the haptic robot, HR). *P1, N2, P3, N4* peak labels. The polarity of the first three deflections detected by electrodes in the posterior half of the head (P1, N2, and P3) was reversed in the anterior leads (N1, P2, N3), while that of the fourth (N4) was not. Note the similarity of the waveforms produced by the HR and actual reaching and the slightly longer latencies of the HR reaching responses. The reference was an average reference of all scalp electrodes



C3
a
1
2
3
12 ms - 112 ms
934 ms - 1034 ms
2664 ms - 2764 ms
C3
b
1
2
3
232 ms - 332 ms
1350 ms - 1450 ms
2820 ms - 2920 ms
-100%
0
100%



a
b
C3
1
2
3
-3000
-2000
-1000
1000
2000
ms
180 ms - 280 ms
822 ms - 922 ms
2830 ms - 2930 ms
1744 ms - 1844 ms
-100%
0
100%

◀ **Fig. 4** Grand averages of the rolandic beta (18–25 Hz) event-related synchronisations and desynchronisations in the C3 derivation (*left*) and their scalp topographies related to the actual (**a**) and haptic robot (**b**) reaching (*right*). Topographies refer to the three 100 ms time intervals denoted by *vertical lines* and numbered from 1 to 3 (*left*). ERDs appeared before target onset. After that they were maximal in the central and parietal electrodes contra-lateral to the reaching arm. At their peaks, ERDs were symmetrical and widely distributed over the occipital, parietal and frontal cortices. ERS rebound appeared only in the actual reaching

motor tasks. The second segment coincided with the movement time (350–620 ms). The average latency differences for each electrode at each time interval were calculated.

Event-related desynchronisation/synchronisation (ERD/ERS)

Peak latencies and amplitudes of the alpha (10–13 Hz) and rolandic beta (18–25 Hz) ERDs were measured for each subject. These latencies in each of the derivations studied were compared between tasks with paired *t* test. Bootstrap method was used to evaluate statistical significance of ERD/ERS differences between tasks [18]. Its main advantage is that it does not require Gaussian or parametric distribution of the data. As suggested by Graimann et al. [18], only significant *t* percentile bootstrap patterns were displayed in the time/frequency map.

Results

Behavioural data

In both groups, mean MT was significantly longer in HR compared to the actual reaching. The mean RTs and errors in performing the tasks did not differ significantly in first group. The second group performed actual reaching significantly more accurately than HR reaching (Table 1).

Event-related potentials

ERPs obtained during actual and HR reaching did not differ essentially in their waveforms (Fig. 2). The ERPs had four distinct peaks. The first three appeared during movement preparation, their latencies being shorter or nearly equal to the RT. The fourth occurred during movement execution. The polarity of the first three deflections detected by electrodes in the posterior half of the head (P1, N2, and P3) was reversed in the anterior leads, while that of the fourth (N4) was not.

Table 2 presents the average latencies and amplitudes of ERPs detected by the central electrodes during the execution of both tasks. ERP amplitudes obtained by the two types of reaching did not differ significantly ($p > 0.05$).

The first two peaks (P1/N1, P2/N2) of ERPs produced by HR reaching were significantly delayed ($p < 0.05$) compared to those obtained by actual reaching (Table 2), whereas those of the two later peaks (P3/N3, N4) did not differ. The latencies of the latter also showed more inter-subject variability.

ERP delays between reaching and HR reaching attained by cross correlation

Results for the central EEG leads are shown in Table 3. No statistically significant ERP delays between reaching and HR reaching could be found in any of the studied time intervals. Variability in the delays between individual subjects was quite high (standard deviations in Table 3).

Event-related desynchronisation/synchronisation in the alpha and beta bands

In the actual reaching, both the alpha and beta ERDs appeared around 2 s prior to the presentation of the target. They were increasing in their sizes until they peaked at around 3 s later. Immediately after target presentation, the alpha and beta ERDs were accentuated focally in the central and parietal leads contra-lateral to the reaching arm while at their peaks their distribution was bilateral and symmetric and were increasingly diminishing in their sizes from the parietal towards both the frontal and occipital derivations (Figs. 3, 4, 5). In the latter, the ERD nearly exclusively appeared in the alpha band. After peaking, ERDs of both bands slowly returned to the baseline. Although maximal desynchronisation was first reached in C3, followed by P1 and F1, we did not find any statistically significant differences in peak latencies between the electrodes (Tables 4, 5).

Shortly after the target onset there was surround ERS in the occipital and frontal leads merely involving beta band (Figs. 4, 5).

The rebound alpha and beta ERSs peaked at around 2,500–3,000 s after target presentation. The alpha ERS was rather generalised while the beta one was more focal and localised to the centro-parietal electrodes contra-lateral to the moving arm (Figs. 3, 5).

We noticed two differences of the ERD/ERS patterns between the actual and HR reaching (Figs. 5, 6, 7). The first one was the size of the alpha and beta ERD obtained by bootstrap analysis, which was larger in case of the actual reaching at around 500 ms after target onset (Fig. 7). Peak ERD amplitudes of the two tasks did not differ significantly. The second, more noticeable difference was much longer duration of the ERD in case of the HR reaching and the absence of ERS in this task (Fig. 7). The duration of the HR reaching ERD exceeded that of the actual reaching by 1,000–2,000 s (not shown in the figures). The HR reaching

ERS was barely noticed only in the contra-lateral centro-parietal leads (again not shown in the figures).

Discussion

Present results suggest that reaching with HR could be used as a substitute for actual reaching in studies of its neural control. Such a conclusion is based on the similarity of behavioural data and rather identical findings of the movement-related ERPs and ERD/ERSs. The shapes and distribution of the ERPs in both tasks were also similar to previous reaching studies performed in humans [7, 8], supporting the reliability of present data. In the following, we shall merely comment on the differences between the actual and HR reaching found in this study.

The reaction times of the actual and HR reaching did not differ significantly in the first group of volunteers. In the

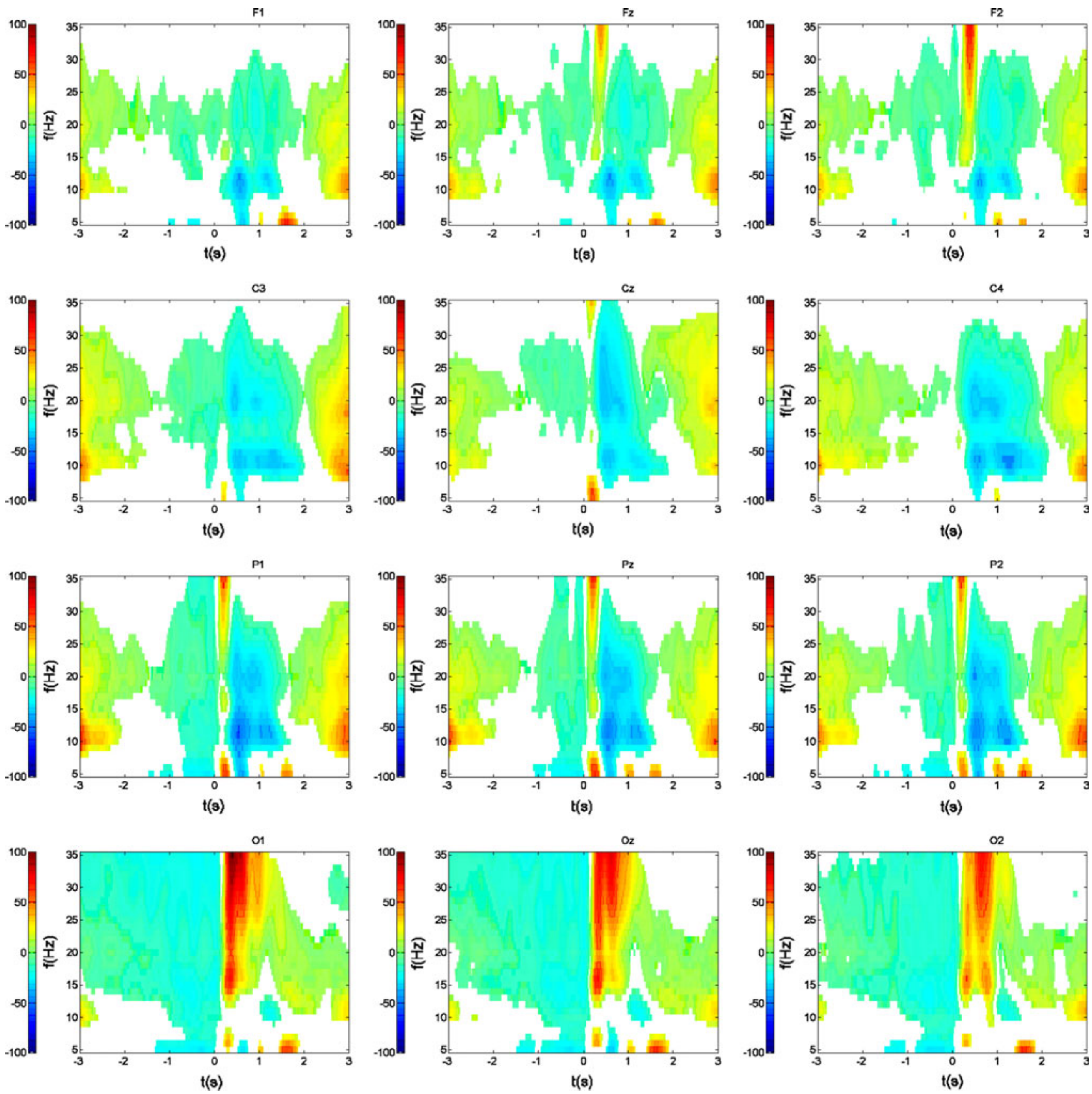


Fig. 5 The actual reaching event related desynchronisation (*negative values*) and synchronisation (*positive values*) time–frequency maps. *Time zero* indicates time of target presentation. Only statistically significant differences from the baseline are plotted

Table 4 Latencies of the maxima of alpha (10–13 Hz) event-related desynchronisations

	Actual reaching		HR reaching	
	Mean (ms)	SD (ms)	Mean (ms)	SD (ms)
F1	822.8*	828.8	2,341	980.2
F2	1,305*	1.152	2,463	835.8
Fz	1,113*	1.048	2,495	838.8
C3	913*	796.8	2,238	958.2
C4	1,384*	852.1	2,538	606.4
Cz	1,191*	856	2,726	699.9
P1	976.2*	709	2,124	997.2
P2	1,061*	720.4	2,201	969.1
Pz	1,063*	746	2,353	960.7
O1	1,685	1,084	2,286	1,072
O2	1,433	1,323	2,190	866.7
Oz	1,706	1,111	2,338	982.8

* Statistically significant differences between actual and haptic robot reaching (paired t test, $p < 0.05$)

Table 5 Latencies of the maxima of rolandic beta spectrum (18–25 Hz) event-related desynchronisations

	Actual reaching		HR reaching	
	Mean (ms)	SD (ms)	Mean (ms)	SD (ms)
F1	1,165*	406.5	2,185	800.3
F2	792*	544.4	1,921	858.4
Fz	951.5*	510.6	1,890	857.8
C3	707*	303.2	1,866	741.1
C4	868.3	381.6	1,335	807.8
Cz	726*	195.5	1,639	996.6
P1	780.3*	351.7	1,626	865.3
P2	806.8*	222.3	1,653	1,037
Pz	730*	283.5	1,715	889.3
O1	875.8	1,054	1,561	1,171
O2	866.5	1,299	1,378	1,070
Oz	1,210	1,208	1,418	962.3

* Statistically significant differences between actual and haptic robot reaching (paired t test, $p < 0.05$)

second group, however, the reaction times of the HR reaching were significantly larger. This group of examinees performed HR reaching more accurately than the first what may be the explanation for their larger RTs. The absolute RT latencies obtained in our study are similar to those obtained in another study where subjects performed almost identical reaching [8].

Movement times of HR reaching were significantly prolonged compared to the actual one in both groups. This disparity may be due to differences in strategies used to perform the tasks. The actual reaching was completed when the index finger touched the screen, even though it did not hit the target. On the other hand, HR reaching was accomplished only after touching the target. If the target was not hit directly, it was reached by fine adjustments of the pointing indicator. The latter movement was therefore slower, more accurate and perhaps necessitated more sensory feedback for its successful accomplishment. In further experiments we should probably introduce a minor change in programming of the virtual environment to compensate for the differences in movement times. Both tasks should have been completed at the same point of task execution. We may not exclude that the differences in MTs may also be due to different strategies in motor programme preparation in the case of instrumental (transitive, HR) reaching. Skilful tool use requires its incorporation into the body's representation, thus enabling decisive manipulation during ongoing acts. This probably takes time to learn well, which was perhaps not possible in our set of experiments. The first task can thus be regarded as a transitive, and the second as an intransitive movement. Further experiments are needed to show whether these differences can be reduced by more extensive pre-trial training.

One of the few important differences of ERPs and ERD/ERSs between the two types of movements was the delay in the first two ERP peaks produced by HR versus actual reaching. This difference was found only by subjective measurements of individual peak latencies and could not be replicated by cross-correlating ERPs. This may be due to very large inter-subject latency differences.

Pre-movement ERD is typical for the self paced movements [19] but we found it also in a stimulus induced reaching movements. Such movements are usually not preceded by ERDs unless they are rhythmic, and therefore, could be anticipated [20]. Such was the case with the inter-reaching intervals in our study, because they varied very little. Alpha and beta ERDs of the actual reaching started in the parieto-central leads contra-laterally to the moving arm. At their peaks, they were bilateral and maximal in the posterior (occipito-parietal) leads but were observed over the sensorimotor and frontal regions as well. Such wide distribution of reaching evoked ERDs compared to those evoked by simple movements (e.g. finger flexions, wrist movements) could be explained by the involvement of more extensive cortical regions in preparation for and during the execution of the former movements [19, 21]. More focal appearance of ERDs, localised primarily to the sensory-motor region, is also typical of the self paced movements that do not engage parietal cortex [19]. In other aspects, the actual reaching ERD/ERSs do not substantially differ from those evoked by other simple reaching tasks ERD/ERS [21–23].

ERD/ERS pattern of the HR reaching was similar to that of the actual one. One of the two differences between the tasks was smaller HR reaching ERD amplitudes in the

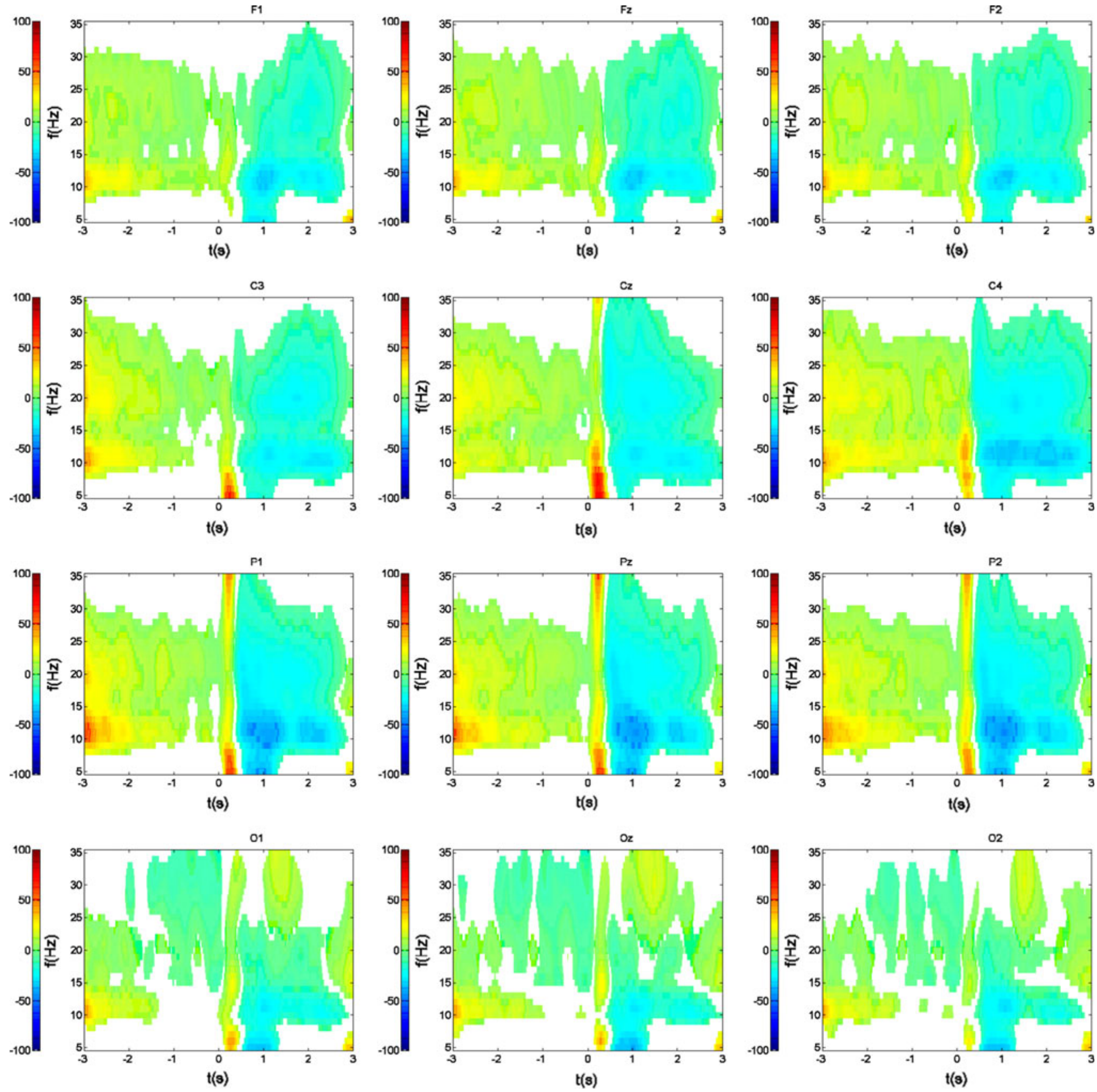


Fig. 6 Haptic robot reaching event related desynchronisation (*negative values*) and synchronisation (*positive values*) time–frequency maps. *Time zero* indicates time of target presentation. Only statistically significant differences from the baseline are plotted

approximately first 500 ms after target onset. The explanation for this may be in the slightly different muscle groups recruited by the two types of movements. In the actual reaching task, bigger muscles and heavier body segments are perhaps engaged to a greater extent compared to HR reaching. Distances to the targets were namely in our experiments slightly longer for this type of movement. As a consequence, a larger size of the motor cortex may be involved evoking larger ERDs.

More pronounced difference between the two reaching tasks was 1 and 2 s longer duration of the ERD in the HR reaching. The explanation for this difference may be longer movement times in the HR reaching what was, at the cortical level, caused by prolongation of the motor cortex activation and longer ERD duration. In the actual reaching, the ERD was followed by rebound ERS while the HR reaching ERS could barely be noticed. Stancka and Pfurtscheller demonstrated that the mu ERD duration is

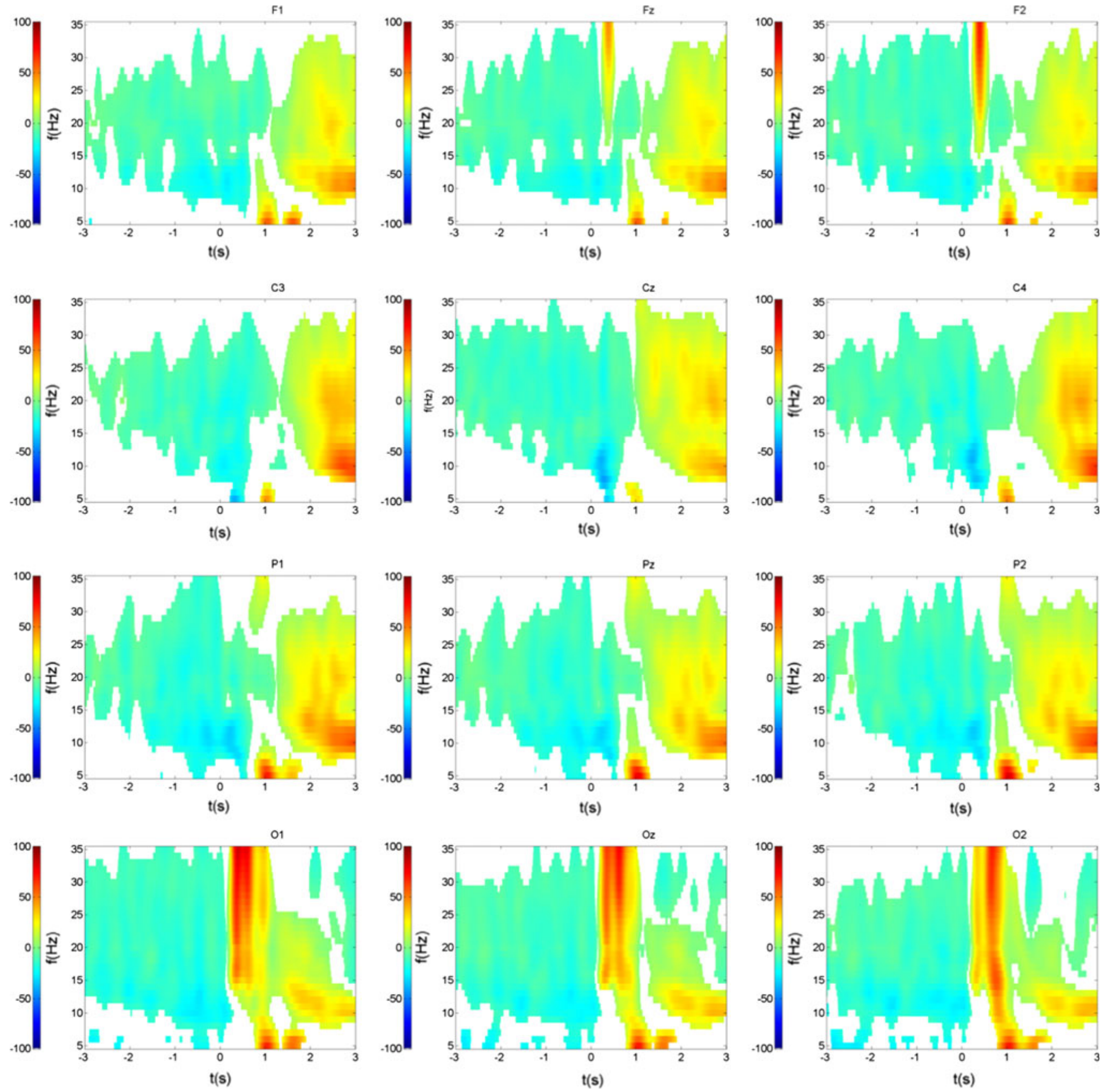


Fig. 7 Bootstrap time–frequency comparison maps of statistically significant differences in the event related desynchronisations/synchronisations (*negative/positive values*) between the actual and haptic robot (HR) reaching. *Time zero* indicates time of target presentation. HR reaching ERD amplitudes were smaller compared to those evoked by actual reaching at around 500 ms after target presentation in the parietal, central and frontal electrodes. The duration of the HR reaching ERD was much longer compared to the one evoked by actual reaching

longer in movements with longer EMG activity [24]. Such movements also evoke later and smaller ERSs, what was explained prolonged activation of motor cortex and greater amount of the afferent input from the limb [25]. We presume that this happened in the HR reaching.

A minor disadvantage of HR reaching may be slightly due to smaller movement amplitude. It is however likely that motor programmes generating movements that vary only in extent (e.g. writing on paper with a pencil versus writing with chalk on the blackboard) do not differ greatly due to motor constancy [26].

We conclude that, regardless of the observed slight differences, HR reaching can be used as a tool for the study of the neural control of reaching. Despite the drawbacks, it offers considerable advantages, of which its compatibility with the MRI setting is most important, together with the possibility to easily introduce interference during movement or precise monitoring the desired direction. All of them might be of assistance in further understanding the properties of motor signals that are elaborated to produce a correct movement.

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