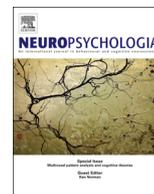




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# How the motor-cortex distinguishes among letters, unknown symbols and scribbles. A high density EEG study



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## ABSTRACT

Previous research has reported that the perception of written language symbols activates the cortical motor hand representation of the dominant hemisphere also found to be activated during the writing of these symbols. It has been suggested that such motor activation supports reading. Nevertheless, the precise circumstances leading to such activation are still unknown. For instance, several studies suggested that motor activation necessarily depends on specific sensory-motor experience with the stimuli. Some results, however, also indicated that untrained stimuli can elicit the response. Moreover, due to the methods used so far, little is known about the temporal course of the motor activity. Our study explored these open questions using high-density EEG. We measured central alpha event-related desynchronization (ERD) as a marker of cortical motor activation during the observation of Roman letters (alphabet of participants' mother language), Chinese characters (not familiar to participants), and scribbles. Our results show that the cortical motor system is activated during the perception of all three stimuli in both hemispheres, with ERD stronger in the left (dominant) hemisphere. A significant difference of ERD time-course was observed in the left hemisphere between the observation of symbols (letters and characters) and scribbles. Scribbles elicited significantly faster resynchronization of central alpha than symbols. We suggest that ERD results are due to recognizing all stimuli as traces of hand gestures. Furthermore, differences in ERD found between symbols and scribbles might depend either on visuo-motor training, separating symbols from scribbles, or on stimuli specific features marking their status as either language symbols or scribbles.

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## 1. Introduction

The neural mechanisms underlying reading have been the subject of a wide range of neuroscientific research (for an overview, see Dehaene, 2007). One of the crucial steps in the process of deciphering a written message is the perception and identification of single written language symbols, such as letters, characters, etc. A number of case studies reported alexia, the inability to read (often caused by the inability to identify single letters), occurring without agraphia, the inability to write (Dejerine, 1892; Friedman & Alexander, 1984; Warrington & Shallice, 1980). Equally, in some cases pure agraphia has been observed (Dubois, Hecaen, & Marcie, 1969; Gordinier, 1899). These reports seem to indicate that reading and writing (or the identification and production of single letters) are dissociable. Yet it should be noted that in most cases alexia is associated with agraphia as well as aphasia. Most interestingly, a specific type of isolated alexia/agraphia, occurring without any

aphasic deficits, has been described (Dejerine & Mirallié, 1885; Benson, 1977). In line with these findings, two independent case studies reported patients with the same cluster of symptoms (Anderson, Damasio, & Damasio, 1990; Starrfelt, 2007). In both cases, patients were completely unable to identify single letters while being able to read Arabic numerals. This impairment was exactly mirrored in the patients' writing skills: while writing letters required time and effort, writing and using numbers in written arithmetic was not problematic at all. The patients showed no aphasic impairments in addition to these deficits. The authors of both studies emphasized that the clinical pictures of their patients hinted at a common mechanism subserving the perception and the production of written language symbols. Starrfelt even suggests that "a deficit in a visuo-motor network containing knowledge of the physical shape of letters might explain the pattern of performance" (Starrfelt, 2007, p. 52).

Interestingly, in both case studies a lesion within the left premotor cortex, in an area often referred to as Exner's area, has been suggested to be mainly responsible for the impairments observed (Starrfelt, 2007). The area originally owes its name to the Austrian physiologist Sigmund Exner who, in 1881, proposed the existence of a cerebral centre for writing located at the foot of the second frontal

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gyrus in the dominant hemisphere (Exner, 1881). This has been supported by recent fMRI studies reporting consistent activations of the cortical hand motor representation during the copying of Japanese characters (Matsuo et al., 2001), as well as during the writing of letters of the Roman alphabet (Longcamp, Anton, Roth, & Velay, 2003, see also James & Gauthier, 2006). Furthermore, Matsuo et al. (2001), Longcamp et al. (2003) as well as James & Gauthier (2006) found a significantly overlapping activation within the cortical hand motor representation during the visual perception of single language symbols (Japanese characters/Roman letters), supporting the hypothesis that a motor activation subserves not only the production but also the perception of these stimuli. Due to the overlapping activations described above, it has been suggested that such a visuo-motor-link could be a crucial component of reading language symbols (Babcock & Freyd, 1988; Freyd, 1983; James & Gauthier, 2009; Longcamp et al., 2003; Longcamp, Tanskanen, & Hari, 2006; Longcamp et al., 2008).

Previous fMRI studies also investigated the effect of training on the motor activation observed during the perception of written stimuli. In their first study investigating motor responses to the perception of written language symbols, Longcamp et al. (2003) found an activation of the cortical hand motor representation only for letters known to participants as parts of their mother language alphabet. They did not find this activation for so-called *pseudo-letters*, “letterlike” stimuli matching common features of language symbols, but not taken from the alphabet of a known language. This finding seemed to support the hypothesis that reading-induced motor activation is not letter/linguistic symbol specific, but merely depends on a specific motor training. This hypothesis was further explored by two fMRI studies (James & Atwood, 2009; Longcamp et al., 2008) comparing areas and strength of BOLD activity during the perception of differentially trained letters/language symbols. Specifically, stimuli comprised “over-learned” characters of participants’ mother language alphabet, new letters (of unknown alphabets) for which participants were trained by writing, new letters for which participants were trained by typing (using a computer keyboard), new letters for which participants were trained only visually, untrained new letters, and geometric shapes. Results of both studies were strikingly similar, showing that only the visual presentation of new letters *trained by writing* elicited left-hemispheric responses similar to activations found during the observation of over-learned letters. The results of both studies support the hypothesis that motor responses found during visual perception of written language symbols depend on motor training (i.e., a certain type of production experience) and are therefore not necessarily letter/written symbol-specific.

Nevertheless this view has been challenged by a study of Wong, Jobard, James, James, and Gauthier (2008) reporting individual differences of the motor response evoked by the perception of previously unknown symbols. Comparing English-Chinese bilinguals and English monolinguals, Wong et al. (2008) showed that while in general activation within the cortical hand motor representation was significantly stronger for symbols of a mother/well known language (group difference), in some monolingual participants not familiar with the writing of Chinese characters this region was equally activated by the visual presentation of Chinese symbols. Similarly, a follow up study of Longcamp, Anton, Roth, and Velay (2005), trying to replicate their previous results in left-handed subjects, showed activation of the cortical hand motor representation not only during the perception of letters, but also of pseudoletters (Longcamp et al., 2005). Furthermore, several studies indicated strong cortical motor modulation due to special visual features of the stimuli. Longcamp et al. (2006) showed that activation of the cortical hand motor representation was significantly stronger if stimuli were handwritten in comparison to printed stimuli (Longcamp et al., 2006), while Matsuo et al. (2001) showed that

modulation of the cortical hand motor representation was enhanced during the observation of visually more complex stimuli (Japanese characters consisting of more strokes).

On the basis of this background it seems reasonable to ask whether the activation of the cortical hand motor representation is in fact necessarily dependent on specific motor training, or if certain visual features of a stimulus are enough to cause the observed cortical motor activation. For example, might it be possible that visual traits marking something as the trace of a prior hand movement (as suggested by the results of Longcamp et al., 2006), or perhaps more specifically as a linguistic symbol (as could be interpreted from the results of Wong et al., 2008 and Longcamp et al., 2005), are sufficient to elicit activation of the cortical hand motor representation?

The study presented here further investigated these questions by comparing the activation of the motor cortex during the perception of handwritten Roman letters (overlearned symbols of participants’ mother-alphabet), Chinese characters (linguistic symbols unfamiliar to participants), and scribbles (stimuli that were regarded by participants as traces of hand movements but not linguistic symbols). By using high density EEG measurements, we specifically assessed for the first time the temporal course of the activation, which is difficult to extract from fMRI data. More specifically, we compared the desynchronization of central alpha (Event-Related Desynchronization, ERD) over 7 consecutive epochs of 250 ms during which participants observed Roman letters, Chinese Characters, and scribbles.

Our hypotheses were the following: If participants’ previously acquired visuo-motor experience evokes central alpha ERD, the latter should occur mainly, if not exclusively, with Roman letters, since they are the only stimuli to be overtrained by participants. However, if the visual features of the stimuli – marking them as possible traces of handwriting – are sufficient to elicit cortical motor activation, then central alpha ERD should be evoked by all stimuli, all of which clearly appear as being hand written. Since a further major difference among the employed stimuli is their symbolic value, present in Roman letters and Chinese characters and absent in scribbles, central alpha ERD modulation in the temporal domain could depend on visual features marking the stimuli as linguistic symbols.

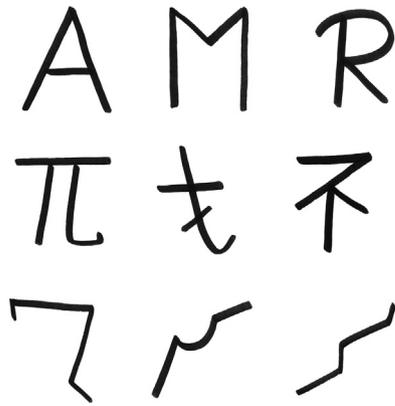
## 2. Materials and methods

### 2.1. Participants

16 healthy volunteers (6 males, 10 females, mean age  $23.5 \pm 8$  years old, all right handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971)), recruited by public announcement, participated in the experiment. One participant was later excluded due to her over-average knowledge of Chinese symbols (tested for in the Rating task, see Sections 2.3 and 4). All participants were paid 15 Euros for reimbursement. Before the experiment, they received written and oral experimental instructions. Written informed consent was obtained from all participants before entering the study. The study was approved by the local Ethical Committee Fig. 1.

### 2.2. Stimuli

Stimuli consisted of 3 groups of 20 written stimuli each, comprising one group of Roman letters, one group of Chinese characters, and one group of scribbles, all matched in size and stroke-number. Under the category “scribbles” we included line formations that, in a prior pilot study, were recognized as traces of writing-like movement, but rated as not being symbols of any language. All 60 stimuli were handwritten by a black felt tip pen of 2.4 mm thickness, then scanned (600 dpi, transformed to avi-format). For EEG recording sessions and rating, digitized stimuli were presented by means of E-prime 2.0 software on a computer screen (resolution  $1280 \times 1024$ ) located at 45 cm from participants.



**Fig. 1.** (a) Examples of Roman letters used (3 out of 20). (b) Examples of Chinese characters used (3 out of 20). (c) Examples of scribbles used (3 out of 20).

### 2.3. Experimental procedure

The experiment consisted of two parts: (1) a 40 min EEG recording; (2) a 10 min rating task.

#### 2.3.1. EEG recording and analysis

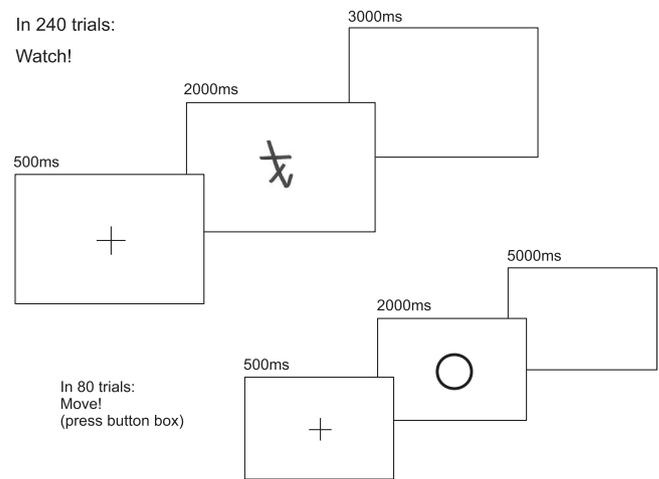
The EEG was recorded during four blocks of about 10 min length each. After each block participants were given the possibility of a break. Each block consisted of 80 trials. Every trial started with the presentation of a fixation cross lasting 500 ms, followed by a stimulus (Roman letter, Chinese character, scribble, or black ring (indicating movement trial, see below)), presented for two seconds at the center of the computer screen. An inter-trial period, serving complete resynchronization of central alpha, in which the screen shone light grey, lasted 3 s in observation-trials, and 5 s in movement-trials (indicated by a black ring, see below).

In 240 trials of the total 320 trials of the experiment the presented stimulus was either a Roman letter, a Chinese character, or a scribble. In 80 trials the presented stimulus consisted of a digitally produced (Photoshop) black ring, matched to other stimuli in size and stroke-thickness. Stimuli presentation was randomized. Participants were given two response options:

(1) If the stimulus consisted of any “black shape” but a ring (thus a Roman letter, a Chinese symbol or a scribble), they were required to simply watch it with attention; (2) If, instead, the stimulus consisted of the black ring, participants were asked to wait until it disappeared and then to press the leftmost key on a button response box placed on the right side of their right hand at a distance of 15 cm. These “movement trials” served to distinguish central alpha from occipital alpha (in occipital regions, movement should not lead to significant alpha desynchronization, while it should in central regions). The decision to let participants press the key only after the ring disappeared was made to avoid action preparation occurring before the appearance of any stimulus (which might lead to a general desynchronization). Furthermore, for the same reason, participants were informed that they did not have to be fast in their response. Fig. 2 shows two example trials of the experiment (observation/movement condition).

#### 2.3.2. Rating task

After the EEG recording session, participants were asked to perform a rating task to test their previous knowledge of the stimuli and their estimation of stimuli’s symbolic value. The stimuli consisted of the 60 stimuli already shown during the EEG recording session (20 Roman letters, 20 Chinese characters, 20 scribbles). The test consisted of two parts. In the first part, each stimulus was presented once at the center of the computer screen. Participants were asked to answer the question: “How likely do you find this shape to be a symbol of a(ny) language? Very much=100, Not at all=0”. The rating was given by moving a cursor shown at the center of a rating scale shown below the stimulus, and ranging from 0 (extreme left) to 100 (extreme right) by use of the mouse. In the second part, participants were presented the same stimuli once again and asked to answer the question: “Do you definitely know that this shape IS in fact a symbol of a(ny) existing language?” The second part was motivated by the necessity to rule out the possibility that some participants had any distinct knowledge of Chinese Characters and would thus be dealing with over-trained stimuli. If participants declared to “know” some Chinese Characters, they were subsequently asked if they had any motor-experience with those characters. Similarly, we wanted to make sure that all participants recognized the Roman letters distinctly as letters and the scribbles as not being letters/symbols.



**Fig. 2.** Setup EEG registration.

**Table 1**

Selected frequency bands.

3 Hz range	8–10 Hz	9–11 Hz	10–12 Hz	11–13 Hz	12–14 Hz
Participant no.	3,1	7,16	15,12,4,5,13	8,1	14,1,2

### 2.4. EEG

EEG data were acquired by a 128-channel Sensor Net (Electrical Geodesic, Eugene, USA) and recorded within a standard EGI package Net Station 4.3.1. EEG was sampled at 250 Hz and band-pass filtered at 0.3–100 Hz; electrode impedance was kept less than 50 k $\Omega$  (controlled after each block). The raw EEG data were recorded with the vertex (Cz) as the online reference and re-referenced off-line to the common average (Muthukumaraswamy, Johnson, & McNair, 2004). Stimuli were presented with E-Prime 2.0. and, at the beginning of each trial, all event markers were sent to Net Station. Participants’ motion was monitored by the experimenter and video-recorded for off-line analysis; if participants moved during the observation or rest conditions, the trial was excluded from further data analysis. EEG data were filtered off-line with band-pass filter 0.3–30 Hz and segmented into specific time epochs. From observation trials the first 1750 ms of stimulus presentation were analysed. Baseline was taken the last 1000 ms of light grey screen (resynchronization period) before the start of the new trial (appearance of the fixation cross) in the observation and movement trials. From movement trials segments of 1000 ms were cut, starting 500 ms before the motor response (button press) and ending 500 ms after it. Only the trials in which participants responded correctly were analysed. The trials in which participants produced eye-blinks and movement artefacts were rejected on the basis of the artefacts detection tool supplied by Net Station as well as on the basis of subsequent careful visual inspection of each segment. A minimum number of 60 trials for each condition was kept (fulfilled by all participants).

The time–frequency analysis was performed by continuous Morlet wavelet transformation in 0.5 Hz intervals in the frequency range from 1 to 30 Hz. Frequency-power coefficients were calculated by taking the average across trials. The wavelet transformation was calculated separately for each participant in all 128 channels for each condition. It was corrected for Baseline (taken out of Fixation cross period) by division (therefore results do not have a unit, see graphics of ANOVAs in Section 4). Statistical analysis was performed on a selected cluster of 6 electrodes in each hemisphere located around standard C3 and C4 sites (Electrodes 30,31,36,37,41,42, left and 80,87,93,103,104,105 right).

For each participant specific alpha-frequency bands were selected in the range of 8–14 Hz following the procedure described in previous studies (Oberman, McCleery, Ramachandran, & Pineda, 2007a; Oberman et al., 2007b). The individual peak (F) of attenuated frequency was determined by calculating a ratio between the frequency power in movement trials and during baseline in the six following sub-frequency bands: 8–14 Hz. Each value was then transformed into a log-ratio and the frequency that corresponded to the log-ratio with the most negative value was taken as F. A 3 Hz range frequency band was chosen for each participant: the interval (F–1; F+1) in which a lower frequency power was revealed in movement trials compared to the baseline. For the following statistical analyses, the frequency power in this 3 Hz range was extracted in all conditions.

Table 1 Since the central alpha frequency band (8–14 Hz) overlaps with the posterior alpha band, it is possible that recordings in central areas might be affected by this posterior activity. In order to check whether the central alpha recorded in central areas was affected by posterior alpha, we performed an

additional analysis in 3 electrodes per hemisphere in occipital areas (electrodes 64, 73, 74 left occipital lobe & electrodes 82, 88, 95 right occipital lobe) using the same frequency bands as previously described.

### 3. Statistical analysis

#### 3.1. EEG recording

In order to assess central alpha desynchronization in sensory-motor areas during different observation and movement trials, we compared the frequency power extracted from wavelet for the different conditions using several ANOVAs.

In order to generally assess central alpha desynchronization in sensory-motor areas, we compared the frequency power extracted from wavelet during baseline (last 1000 ms of period of light grey screen before fixation cross) with that during observation conditions (1750 ms in total—the last 250 ms had to be left out due to the wavelet artifact) and movement (500 ms before and after button press) using a  $2 \times 5$  ANOVA with two levels of Hemisphere (right vs. left) and 5 levels of Condition (baseline, three observation conditions (letters, characters, scribbles) and movement). To be sure that our baseline was stable we also extracted the frequency power in the four single epochs of 250 ms making up the total of 1 s and compared the results for each of these epochs.

In order to assess the time course of central alpha desynchronization in sensory-motor areas during the three observation conditions, we used a  $2 \times 3 \times 7$  ANOVA with 2 levels of Hemisphere (right vs. left), 3 levels of Condition (Roman letters, Chinese characters, scribbles), and 7 levels of Time (7 epochs of 250 ms). To keep the relation to baseline in the picture, values used for this ANOVA were the log values of the condition/baseline division. For the baseline, for which we had only 1000 ms of recording, we always divided by the average of these 1000 ms (for each participant and hemisphere).

To control for effects in occipital electrodes both of the ANOVAs described above were repeated for the occipital electrodes.

#### 3.2. Rating task

For the first question results were analysed using an ANOVA with the single main factor of Condition (3 levels). For the second question, we only counted the amount of stimuli for which participants answered that they knew for sure that they were symbols of an existing language.

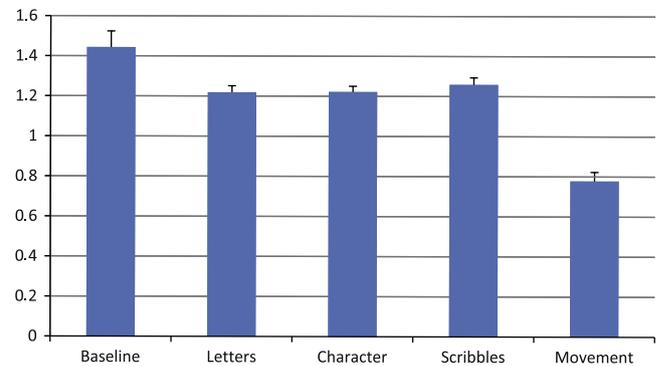
In all performed ANOVAs we applied Fisher's post-hoc Test to all significant factors and interactions.

## 4. Results

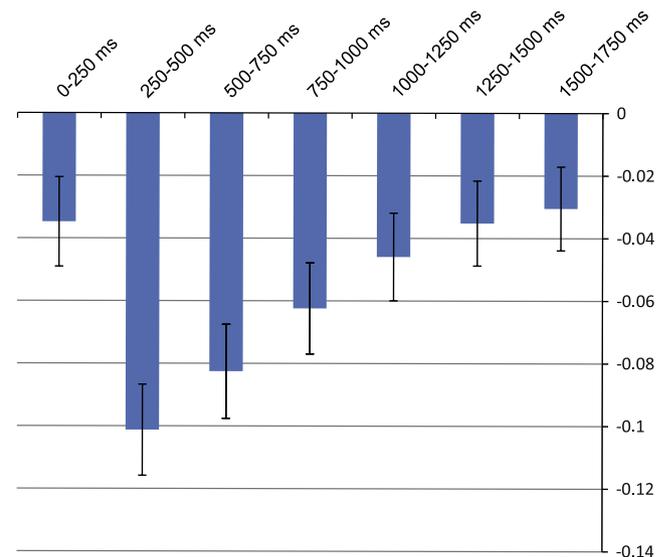
#### 4.1. EEG measurements

##### 4.1.1. General assessment

We first controlled for the stability of baseline (last second of light grey screen at the end of trial) by extracting the frequency power of alpha in central electrodes for each of the four 250 ms epochs making up the whole second of baseline-recording and comparing the results. A  $2 \times 4$  ANOVA with two factors of Hemisphere (left and right) and 4 factors of Time (4 epochs of 250 ms each) showed no significant effect for single factors or interactions (For Hemisphere:  $F(1,14)=0.0032$ ,  $p > 0.95$ ; for Time:  $F(3,42)=1.2759$ ,  $p > 0.29$ ; for Hemisphere\*Time interaction:  $F(3,42)=1.1369$ ,  $p > 0.34$ ). In order to generally assess central alpha desynchronization (Event-Related Desynchronization, ERD) in sensory-motor areas, we compared the frequency power extracted from wavelet during baseline (one second of light grey screen) with that



**Fig. 3.** Averages of frequency power alpha in central electrodes over whole time span of registration of single conditions (1 s of baseline (grey screen at the end of resynchronization-period), 1.75 s of shape observation (letters, characters, scribbles), 1 s of movement (0.5 s before and after button press)).



**Fig. 4.** Time course of ERD during observation conditions over 7 epochs of 250 ms each.

during observation conditions (Roman letters, Chinese characters and scribbles during whole time of 1750 ms of observation), and that during movement (500 ms before and after button press). Descriptives (see Fig. 3) showed that compared to baseline ERD was present in all three observation conditions, with a maximum in the movement condition. A  $2 \times 5$  ANOVA (Hemisphere  $\times$  Condition) showed only a significant main effect for Condition ( $F(4,56)=18.043$ ,  $p < 0.001$ ).

Post-hoc Comparisons showed that significant differences concerned baseline compared with all other conditions and movement compared with all other conditions (for all these comparisons  $p < 0.001$ ). Differences between different observation-conditions were not significant (for all  $p > 0.6$ ).

##### 4.1.2. Observation trials

In order to assess the precise time-course of ERD in sensory-motor areas during the three observation conditions, we compared the log values of the frequency power extracted from wavelet during the different observation conditions divided by baseline. A  $2 \times 3 \times 7$  ANOVA design was created with 2 levels of Hemisphere (left vs right), 3 levels of Condition (Roman letters, Chinese characters and scribbles) and 7 levels of Time (7 epochs of 250 ms). The results of the ANOVA revealed a significant main effect of Time ( $F(6,84)=15.75544$ ,  $p < 0.001$ ) as well as significant

interactions of Hemisphere\*Time ( $F(6,84)=8.60049, p < 0.001$ ) and Hemisphere\*Condition\*Time ( $F(12,168)=2.10714, p < 0.05$ ).

Descriptives regarding the main effect of Time (see Fig. 4) showed that ERD was strongest in the second epoch (250 ms to 500 ms), followed by a steady resynchronization reaching the level of epoch 1 in epoch 5.

Descriptives regarding the effect of Hemisphere\*Time interaction (see Fig. 5) showed that in all observation conditions, taken together, ERD was stronger in the left hemisphere than in the right hemisphere during the first 3 epochs.

Post-hoc comparisons showed that these differences were significant for all these 3 epochs ( $p < 0.001$ ).

Descriptives and posthoc comparisons regarding the interaction of Hemisphere\*Condition\*Time (see Fig. 6a and b) showed the following two main characteristics: First, it could be seen that until the fourth epoch ERD measured in the left hemisphere was significantly stronger than in the right hemisphere for all three conditions (Roman letters, Chinese characters, and scribbles). Furthermore, only in the left hemisphere could we observe a clustering for letters and characters, especially concerning the resynchronization phase. Indeed, in the left hemisphere central alpha during the observation of scribbles resynchronized significantly faster than during the observation of symbols in general (Roman letters and Chinese characters).

Results for the single epochs show the following. First epoch (0–250 ms): ERD for all conditions was stronger in the left hemisphere ( $p < 0.001$ ). In the left hemisphere ERD was strongest during the observation of scribbles, weakest during the observation of letters. Post-hoc comparisons showed that only the difference between scribbles and letters was significant ( $p < 0.05$ ). In the right hemisphere (Fig. 6b) ERD was strongest during the observation of letters, weakest during the observation of scribbles. Post-hoc comparisons showed significant differences between scribbles and the other two categories of stimuli ( $p < 0.05$ ).

Second Epoch (250–500 ms): ERD for all conditions was stronger in the left hemisphere ( $p < 0.001$ ). In both hemispheres ERD was strongest during the observation of letters, weakest during observation of scribbles. In both hemispheres this difference was significant between scribbles and letters ( $p < 0.05$ ).

Third Epoch (500–750 ms): ERD for all conditions was stronger in the left hemisphere ( $p < 0.001$  for letters,  $p < 0.01$  for characters,  $p < 0.05$  for scribbles). In both hemispheres ERD was strongest during observation of letters, weakest during the observation of

scribbles. In the left hemisphere these differences were significant between scribbles and the other two categories of stimuli ( $p < 0.001$ ). In the right hemisphere the only significant difference was between letters and scribbles ( $p < 0.05$ ).

Fourth epoch (750–1000 ms): There was no longer any significant difference in conditions between hemispheres. In both hemispheres ERD was strongest during the observation of letters, weakest during the observation of scribbles. In the left hemisphere differences were significant between scribbles and the other two categories of stimuli ( $p < 0.001$ ). In the right hemisphere differences were significant between letters and scribbles only ( $p < 0.05$ ).

Fifth epoch (1000–1250 ms): There was no longer any significant difference in conditions between hemispheres. In the left hemisphere ERD was strongest for characters and weakest for scribbles. These differences were significant between scribbles and the other two categories of stimuli ( $p < 0.01$  for letters,  $p < 0.001$  for characters). In the right hemisphere ERD was strongest during the observation of letters, weakest during observation of scribbles. These differences were significant between letters and scribbles ( $p < 0.05$ ).

Sixth epoch (1250–1500 ms): There was no longer any significant difference in single conditions between hemispheres. In the

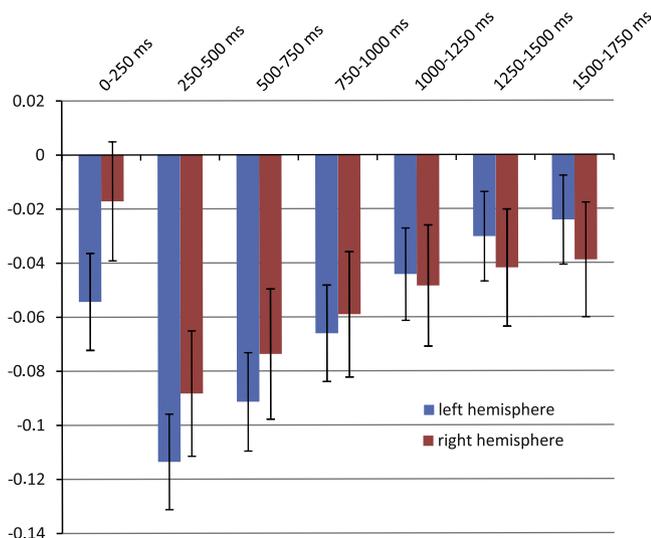


Fig. 5. Time course of ERD during observation conditions over 7 epochs of 250 ms in single hemispheres.

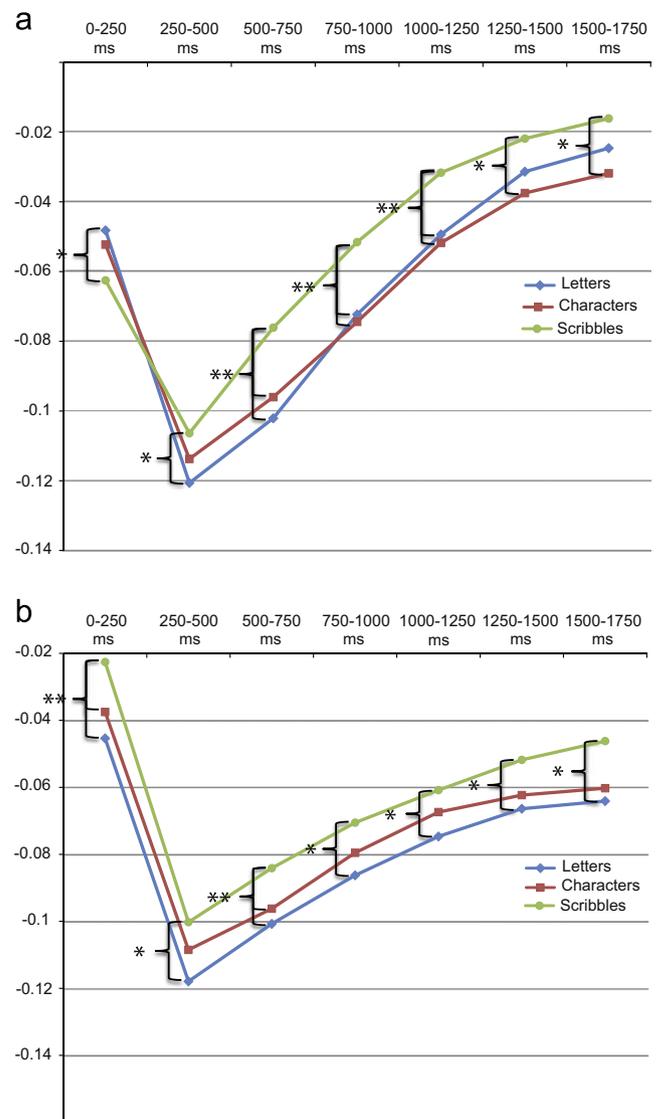


Fig. 6. (a) Time course of ERD during observation conditions over 7 epochs of 250 ms in single conditions, left hemisphere. (b) Time course of ERD during observation conditions over 7 epochs of 250 ms in single conditions, right hemisphere.

left hemispheres ERD was strongest for characters and weakest for scribbles. The only significant difference was between characters and scribbles ( $p < 0.01$ ). In the right hemisphere ERD was strongest for letters and weakest for scribbles. The only significant difference was between letters and scribbles ( $p < 0.05$ ).

**4.1.2.1. Seventh epoch.** There was no longer any significant difference between hemispheres. In the left hemisphere ERD was strongest for characters and weakest for scribbles. The only significant difference was between characters and scribbles ( $p < 0.00$ ). In the right hemisphere ERD was strongest for letters and weakest for scribbles. Differences were significant between letters and scribbles ( $p < 0.05$ ) and characters and scribbles ( $p < 0.05$ ).

#### 4.1.3. Control occipital

To control for effects in occipital regions we repeated the analysis performed for central electrodes and looked for significant differences between regions (central and occipital electrodes).

A  $2 \times 5$  ANOVA with 2 factors of Hemisphere and 5 factors of Condition (Baseline, Roman letters, Chinese characters, scribbles and movement) in the occipital region showed a main effect of Condition ( $F(4,56)=5.72856$ ,  $p < 0.001$ ) Fig. 7.

Post-hoc comparisons (Fisher-tests) revealed that the only significant difference was between baseline and all other conditions ( $p < 0.001$ ). There were no significant differences among the three different observation conditions or among any observation condition and the movement condition (for all  $p > 0.8$ ). These results show that in contrast to central alpha, occipital alpha showed no further desynchronization in the condition of movement.

For the second analysis we again calculated the log values of the frequency power extracted from wavelet during the different observation conditions in occipital electrodes divided by the respective baseline in occipital electrodes ( $\log(\text{observation-value}/\text{baseline-value})$ ). A  $2 \times 3 \times 7$  ANOVA with 2 factors of Hemisphere, 3 factors of Condition (Roman letters, Chinese characters and scribbles) and 7 factors of Time in the occipital region showed only a significant main effect of Time ( $F(6,84)=6.15135$ ,  $p < 0.001$ ). Descriptives regarding the main effect of Time (see Fig. 8) showed that ERD was strongest in the second epoch (250 ms to 500 ms), followed by a steady resynchronization.

The two analyses performed on occipital electrodes clearly showed that occipital alpha is modulated by the presentation of any visual stimulus, independently of their specific nature.

#### 4.2. Rating task

Results of the ratings of question one (“How likely do you find it, that this shape could be a symbol of a(ny) language? Very

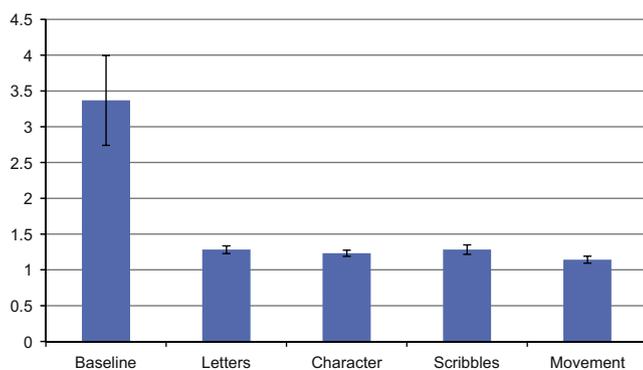


Fig. 7. Averages of frequency power alpha in occipital electrodes over whole timespan of registration of single conditions.

much=100, Not at all=0”) showed that participants rated letters (from the Roman alphabet, thus their mother tongue) more likely to be symbols of a(ny) language, than Chinese characters, and Chinese characters more likely to be symbols of a(ny) language than scribbles.

(MS(Letters): 92.73, STE:1.25; MS(Character):62.41, STE: 3.84; MS(Scribbles):18.95, STE: 2.49) A One-way ANOVA with the single factor of CONDITION (letters, characters, scribbles) showed a main effect ( $F(2,30)=264.414$ ,  $p < 0.001$ ). Post-hoc comparisons (Fisher-tests) confirmed that all differences were significant ( $p < 0.001$ ). The fact that Roman letters were not always rated as 100% likely to be symbols of a language could be attributed to two facts. First, participants voted on a whole scale from 0–100 and were explicitly asked to use the scale as a whole (so not always to give an answer of 0 or 100). As a result, the voting of 100 was rather rare. Second, the results of the second question (“Do you know (definitely) that this shape IS in fact a symbol of a(ny) existing language?”) showed that on average participants declared to know 18 (out of 20) letters as definitely being a symbol of any language (MS:18.21; STE:0.14). This is likely to be due to the way the letters were handwritten, which may have left certain participants in doubt about whether they had in fact been presented with a certain known Roman letter. One letter (J) that was not definitely recognized by more than 50% of participants was consequently excluded from EEG analysis.

Results to question 2 revealed that participants on average did declare to know 3 Chinese characters as being symbols of an existing language (MS: 3.14, STE: 0.6). However, to the further question if they had any writing experience with the respective characters, participants all answered negatively. The stimuli were consequently left in the pool for EEG analysis. Nevertheless, one participant that declared to definitely know 10 Chinese characters in total ( $> \text{MS}+2$  Standard deviations) and that they belonged to the Chinese language was excluded from the analysis.

## 5. Discussion

Analysis of the present EEG data showed that the observation of all stimuli (letters, characters and scribbles) produced central alpha ERD in both hemispheres, distinguishable from ERD in occipital regions. As expected from previous research, desynchronization was generally stronger in the left (dominant) hemisphere. These results support the main hypothesis generated by previous (fMRI) studies (see for example Matsuo et al., 2001; Longcamp et al., 2003; James & Gauthier, 2006) that there is an action-perception link subserving the production as well as the perception of written language symbols.

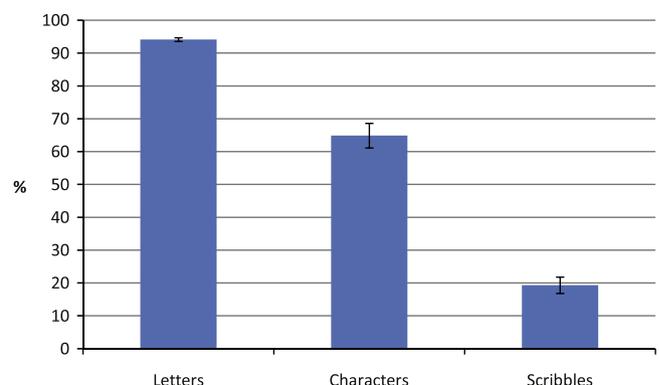


Fig. 8. Results rating task “How likely do you find this shape to be a symbol of a(ny) language?”.

Moreover, since the mean values of central alpha frequency power indicate an ERD also during the perception of “scribbles”, our data seems to support the notion that not only linguistic symbols, but any possible hand-gesture trace (see also Umiltà, Berchio, Sestito, Freedberg, & Gallese, 2012) can evoke the activation of observers’ cortical motor system. Nevertheless, our analysis of the ERD time-course shows significant differences among stimuli groups that ask for further discussion.

It should be noted that our analysis did not find significant differences between overtrained symbols (letters) and untrained symbols (chinese characters), neither considering the total time of stimulus presentation nor single epochs. However, three previous fMRI studies (Longcamp et al., 2003, 2008; James & Atwood, 2009) showed that, when comparing visually trained and untrained letters/pseudoletters with letters *trained by writing*, only the latter elicited left-hemispheric responses similar to the activations found during the observation of over-learned letters. Thus, it seems likely that our results showing an apparent lack of training effects might be due to the different type of stimuli and/or technique we employed.

Regarding the first possibility (differences to prior studies due to stimuli-choice), Wong et al. (2008) have already suggested that some of the Chinese characters used in their study embedded stroke-formations partly resembling roman letters. In this case the effect of overtraining for the letters might affect the “untrained stimuli” (characters), and in so doing might conceal actual differences between conditions. This effect in our study could even be enhanced by the fact that all stimuli were handwritten by the same person and thus shared certain characteristics of stroke-gesture, etc. If this interpretation is correct, a “training effect” might also be seen in our study when considering the different ERD time-courses during the observation of letters and characters, clustered together, and scribbles. Indeed, our results show that despite the fact that all stimuli elicited a central alpha ERD, central alpha showed a slightly weaker desynchronization during the observation of scribbles compared to during the observation of letters as well as a significantly faster resynchronization during the observation of scribbles in comparison to the observation of both, letters and characters. These results seem to indicate that (direct or indirect) sensory-motor experience with stimuli leads to a partly stronger and significantly more prolonged central alpha desynchronization during the perception of these stimuli.

Regarding the second possibility (differences to prior studies due to technique), it should be stressed that the methods used are different (ERD vs. fMRI) and measure different types of neural responses. Hence it might indeed be possible that, in contrast to the BOLD signal, central alpha ERD is not significantly modulated by sensory-motor training. We therefore suggest that our results likely do not contradict the findings of Longcamp, James and colleagues: rather they add new information and pose new questions regarding motor cortex responses to symbolic stimuli and the different ways to measure these responses.

In line with this remark, we would lastly like to emphasize that our EEG results clearly show that the employed stimuli fall into two distinct groups: language symbols and scribbles. Central alpha showed a slightly weaker desynchronization during the observation of scribbles compared to during the observation of letters as well as a significantly faster resynchronization during the observation of scribbles in comparison to the observation of both, letters and characters. It is possible that language symbols share visual features which are the outcome of the way they are written and which precisely make them recognizable as symbols (not scribbles). As another interpretation of our results we would therefore like to suggest that these features (independent from training) could be the reason for their stronger impact on observers’ cortical motor system, visible in the time-course central alpha desynchronization. This admittedly bold hypothesis perhaps finds some

support from previous empirical evidence and the further findings of our study. First, previous MEG as well as fMRI studies have indeed found an influence of visual features on motor cortical response. Longcamp et al. (2005) showed by means of MEG recording stronger central ERD for observed handwritten letters than for observed printed letters. Furthermore, Matsuo et al. (2001) showed by means of fMRI that activation in the cortical motor hand representation correlated with stimuli visual complexity (more complex Japanese characters elicited stronger activation than less complex ones). Finally, in our rating task scribbles were always recognized by participants as a trace of hand movement (writing/scribbling). However, they were rated significantly much less likely to be a symbol of any existing language, which supports the assumption that visual features do not make them recognizable as a symbol. If, as suggested by several prior studies (Babcock & Freyd, 1988; Freyd, 1983; James & Gauthier, 2009; Longcamp et al., 2003, 2006, 2008), the action-perception link observed for letters serves stimulus recognition important for reading, this might lead to different activations of this link.

That said, it must be stressed that the setup of our experiment does not allow further specification of which visual features possibly cause the suggested difference in the perception of letters/characters and scribbles, thus clearly asking for further research. In this context special care should be paid on further exploring the precise temporal characteristics of the ERD elicited by the stimuli revealed by our study: the main differences found regarding the ERD time-course during the observation of scribbles in comparison to the observation of linguistic symbols concern the resynchronization phase of central alpha frequency bands. Previous research has suggested that the resynchronization of the mu rhythm is connected to an active inhibition of the motor-cortex activation (Klimesch, Sauseng, & Hanslmayr, 2007). More interestingly even, in this context, modulations of this resynchronization phase of the mu-rhythm have been repeatedly found to differentiate among conditions that nevertheless all evoked a significant ERD due to an action-perception link (see for example Koelewijn, van Shiie, Bekkering, Oostenveld, & Jensen, 2008). We would therefore like to suggest that our data might indicate that the response of the motor system can in fact be regulated by the inhibition of the activation initially evoked rather than by a modulation of its initial activation. It might very well be the case that earlier and stronger resynchronization due to this inhibition accounts for the differences found in previous (fMRI) studies. To investigate this hypothesis further experiments comparing handwritten symbols, scribbles and other control-stimuli (as printed letters/shapes etc.) are necessary.

In conclusion, our study supports the hypothesis that the cortical motor system is activated during the perception of written language symbols, representing a visuo-motor link between production and perception of these shapes. Moreover, we show for the first time that the perception of “scribbles” initially also evokes the activation of observers’ cortical motor system, indicating that motor activation can be elicited by any possible trace of hand-movement. However, differences were found between stimuli-groups regarding the specific time-course of the activation: desynchronization of central alpha elicited by the observation of scribbles was slightly weaker than elicited by letters. Most importantly however, the resynchronization happened significantly faster than during the observation of Chinese characters and Roman letters. We suggest that this differential activation might depend on either sensory-motor training in a broad sense, separating symbols in general from scribbles, or on visual features allowing a categorical distinction between symbols and scribbles, leading to the difference observed. Both these possibilities should be further explored by future research to enhance our knowledge about central alpha ERD as a specific marker of cortical motor

activity, as well as to further investigate the activation of the motor cortex during the perception of written language symbols and other traces of handwriting.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.neuropsychologia.2013.07.014>.

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