

Neurophysiological Distinction of Action Words in the Fronto-Central Cortex

Olaf Hauk* and Friedman Pulvermüller

Medical Research Council, Cognition and Brain Sciences Unit, Cambridge, United Kingdom

Abstract: It has been suggested that the processing of action words referring to leg, arm, and face movements (e.g., to kick, to pick, to lick) leads to distinct patterns of neurophysiological activity. We addressed this issue using multi-channel EEG and beam-former estimates of distributed current sources within the head. The categories of leg-, arm-, and face-related words were carefully matched for important psycholinguistic factors, including word frequency, imageability, valence, and arousal, and evaluated in a behavioral study for their semantic associations. EEG was recorded from 64 scalp electrodes while stimuli were presented visually in a reading task. We applied a linear beam-former technique to obtain optimal estimates of the sources underlying the word-evoked potentials. These suggested differential activation in frontal areas of the cortex, including primary motor, pre-motor, and pre-frontal sites. Leg words activated dorsal fronto-parietal areas more strongly than face- or arm-related words, whereas face-words produced more activity at left inferior-frontal sites. In the right hemisphere, arm-words activated lateral-frontal areas. We interpret the findings in the framework of a neurobiological model of language and discuss the possible role of mirror neurons in the premotor cortex in language processing. *Hum. Brain Mapp.* 21:191–201, 2004. © 2004 Wiley-Liss, Inc.

Key words: language perception; EEG; semantics; cell assemblies; mirror neurons; beam-former estimates

INTRODUCTION

Neuropsychological and imaging studies of the last two decades revealed evidence that numerous cortical areas are involved in the processing of concepts and word meanings [Humphreys and Forde, 2001]. This can be explained by assuming that one organization principle of the brain is that of an associative memory [Braitenberg and Schüz, 1998; Fuster, 1995], and that semantic information is stored by

strengthened synaptic connections between neurons in core language areas in the left hemisphere, and complementary language areas processing information about objects and actions the words refer to [Pulvermüller, 2001]. For words that refer to objects that are usually visually perceived (e.g., “sun”), complementary language areas would be the visual cortices in the inferior temporal and occipital lobes, and for action words (e.g., “to walk”) these would be motor, pre-motor, and pre-frontal areas. Neuropsychological double dissociations in patients and differential cortical activation revealed by neuroimaging studies have provided support for this view [Humphreys and Forde, 2001; Martin et al., 1996; Kiefer, 2001; Perani et al., 1999; Pulvermüller, 1999; Warrington and McCarthy, 1996].

Category differences may exist, at an even finer scale, between semantic subcategories of action words. If action words are processed by distributed cell assemblies that include action-related neurons in frontal lobes, the body parts with which the referent actions are executed should be reflected in corresponding word-evoked brain responses [Pulvermüller, 1999]. The somatotopic organization of the motor and premotor cortex implies that actions performed with

Contract grant sponsor: Medical Research Council; Contract grant sponsor: European Community, “Information Society Technologies Programme”; Contract grant sponsor: IST-2001-35282

*Correspondence to: Olaf Hauk, Medical Research Council, Cognition and Brain Sciences Unit, 15 Chaucer Road, Cambridge CB2 2EF, UK. E-Mail: olaf.hauk@mrc-cbu.cam.ac.uk

Received for publication 2 December 2002; Accepted 5 November 2003

DOI 10.1002/hbm.10157

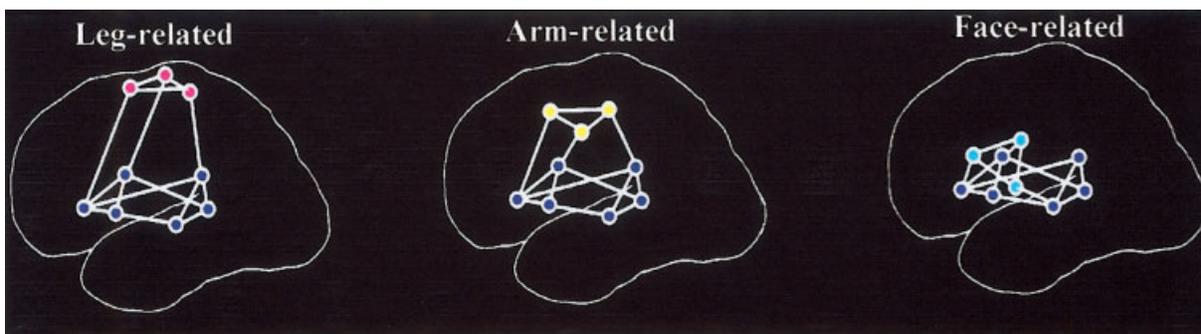


Figure 1.

Illustration of our hypothesis: Action words are represented by cell assemblies comprising neurons in the core language areas and additional neurons in motor areas in the frontal cortex controlling movements carried out with the corresponding body parts.

different body parts relate to different topographic patterns of activation in motor, pre-motor, and adjacent prefrontal areas. Somatotopic organization has been demonstrated for the primary cortex [Penfield and Rasmussen, 1950] and could be revealed for more rostral frontal areas, in particular for premotor areas, as well [He et al., 1993; Rizzolatti et al., 2001]. In the primary motor cortex, the leg representation is to a great extent hidden in the interhemispheric sulcus, but premotor representations of the legs are also found on the lateral surface of the frontal lobe, where they are located superior to the hand representation anterior to the precentral gyrus. In both the precentral gyrus and the premotor areas, the representation of arm and hand movements is lateral and inferior to that of leg movements. If action-related information is woven into the cortical neuron webs representing and processing words, one would predict that words referring to different body parts may correspond to networks with different cortical distributions. As illustrated in Figure 1, the action-related neurons of a word referring to a leg movement, such as “to kick,” should be dorsal to those of a word related to a movement involving face and articulator muscles, as, for example, “to lick.” The semantic difference between subcategories of action words should thus be laid down in the cortical distribution of word-related neuron webs, a hypothesis that has clear implications for neurophysiological brain research on language.

In this study, we investigated brain activity elicited during the reading of action words that refer to face-, arm-, and leg-movements. Word processing is a fast process. Upon visual presentation of a word, information about its form and meaning is accessed within ~200 msec [Marslen-Wilson and Tyler, 1980; Pulvermüller, 2001]. To precisely follow this rapid time course of word-evoked cortical activity, we chose event-related potentials recorded through multi-channel EEG as the dependent measure. Source current estimates were performed on the ERP topographies to reveal clues about the cortical loci where such fast activity is being generated. Source current estimates provide an objective way of localizing distributed cortical sources in the brain

that underlie the EEG and MEG signal [Dale and Sereno, 1993; Hämäläinen and Ilmoniemi, 1994].

It has been shown in a variety of studies that ERP methodology is suitable to reveal word category differences in the human brain [Dehaene, 1995; Kiefer, 2001; Pulvermüller et al., 1999]. A recent study by Pulvermüller et al. [2001] suggested that action words of different types may become neurophysiologically distinct around 200 msec after their presentation. We now looked at face-, arm-, and leg-related words paying special attention to the following important methodological issues:

1. Whereas many earlier studies used tasks requiring an overt response (button press) that are likely to influence neuronal activity in the motor system, we now used a passive reading task and instructed our subjects not to move during the experiment. This issue is important theoretically, because some models [Pulvermüller, 2001; Rizzolatti and Luppino, 2001] suggest that the perception of action-related words gives rise to activity in the fronto-central motor system, regardless of whether an overt response is required or not.
2. Word stimuli were carefully matched for crucial psycholinguistic and psychological variables, in particular word frequency, word length, imageability, valence, and arousal. These variables are reflected in the brain response and must, therefore, be controlled for, although this has not always been the case in previous imaging studies [for discussion, see Assadollahi and Pulvermüller, 2001; Kiefer and Spitzer, 2001].
3. The semantic properties and associations of our stimuli (arm-, face-, leg-relatedness) were carefully evaluated with behavioral tasks, and only words with well-defined semantic and referential features entered the neurophysiological study.
4. For objectively estimating the activity of the multiple current sources underlying word evoked neurophysiological activity, we used a linear estimation or “beamformer” technique, to obtain estimates of brain activity

for individual subjects and conditions. The estimators are created such that estimates for different source locations are optimally independent in a well-defined sense [Baillet et al., 2001; Grave de Peralta et al., 1997; Sekihara et al., 2002]. These source estimates were subjected to group statistical analysis to test our hypotheses. Source localization estimates at the single subject level and their statistical evaluation are necessary for revealing effects that are consistently present in a larger subject population.

SUBJECTS AND METHODS

Subjects

Twelve monolingual native speakers of English (7 females, 5 males) participated in the study. Their age varied between 18 and 31 years (mean 22.4, SD 3.7 years). They spent a minimum of 13 years on basic and higher level education. All had normal or corrected-to-normal vision and reported no history of neurological illness or drug abuse. Neuropsychological testing [Oldfield, 1971] revealed that all of them were right-handed (mean laterality quotient 87, SD 16). Four volunteers reported they had one left-hander among their close relatives. Informed consent was obtained from all subjects and they were paid for their participation. This study was approved by the Cambridge Psychology Research Ethics Committee.

Stimuli

Stimuli were selected from databases using psycholinguistic criteria. A preliminary list of 403 words was evaluated in a behavioral study to assess the words' cognitive, emotional, and referential-semantic properties. This is necessary because words differing on corresponding dimensions are known to elicit different neurophysiological responses [Kounios and Holcomb, 1992; Pulvermüller, 1999; Skrandies, 1998]. Native speakers of English (N = 15, different from those participating in the EEG study) gave ratings on a 7-point scale answering the following questions:

- "Does this word remind you of an action you could perform with your arms, hands, or fingers?" (Arm-relatedness)
- "Does this word remind you of an action you could perform with your feet, legs, or toes?" (Leg-relatedness)
- "Does this word remind you of an action you could perform with your head, face, or mouth?" (Head-relatedness)
- "How easily does this word evoke an image or any other sensory impression?" (Imageability)
- "Do you evaluate this word or its meaning as pleasant or unpleasant?" (Valence)
- "How arousing is this word or its meaning?" (Arousal)

Ratings were given on a scale from 1 (e.g., "does not remind me at all") to 7 (e.g., "reminds me very much"). The results were evaluated statistically using F-tests. On the

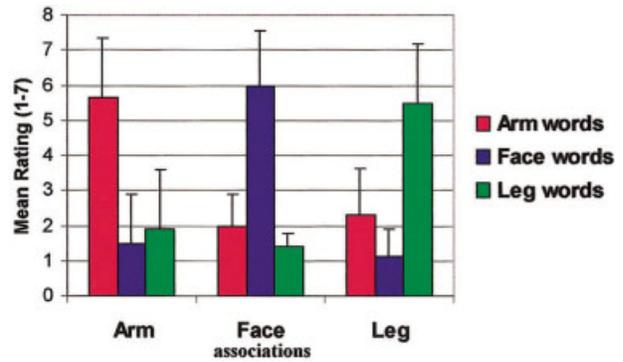


Figure 2.

Mean rating scores for the dimensions arm-, face-, and leg-relatedness (with standard deviations) obtained in a word rating experiment. Ratings were given on a scale from 1 to 7.

basis of this evaluations, we selected 50 arm-, 50 head-, and 50 leg-related items for presentation in the EEG experiment, interspersed with 150 distractor words not related to actions. The word groups were matched with respect to mean word-length (arm: 4.46 letters, face: 4.55, leg: 4.64), word form frequency according to the CELEX database [Baayen et al., 1993] (arm: 13.7 per million, face: 13.7, leg: 13.9), imageability (arm: 4.7, face: 4.5, leg: 4.6), valence (arm: 3.6, face: 3.6, leg: 3.9), and arousal (arm: 3.6, face: 3.2, leg: 3.6). All of the action words included in the study could be used as verbs. As most words in English are lexically ambiguous (they may be used, for example, as nouns or verbs), this was also true for 86% of the words in the stimulus set (arm: 42 items, face: 43 items, leg: 44 items; determined according to CELEX). Importantly, the 3 action word groups differed maximally on the dimension face-, arm-, and leg-relatedness. An ANOVA including the factors WORD TYPE and ASSOCIATION revealed a highly significant interaction between these factors ($F(4,196) = 881.86$, $P < 0.001$). The mean rating scores are presented in Figure 2. This shows that, for example, the leg words were much more strongly associated with leg/foot movements than with movements of other body parts. In the same way, the face- and arm-words elicited specific face and arm associations, respectively.

Procedure

Stimuli were presented for 100 msec each in white capital letters on a gray background in the middle of a computer screen, subtending a horizontal visual angle smaller than 5 degrees. A fixation cross was always present in the center of the screen between stimulus presentations. Subjects were instructed to read the stimulus words silently, i.e., no overt response was required. Stimuli were presented in pseudo-random order with a stimulus onset asynchrony randomly varying between 2 and 3 sec. Two pseudo-randomized lists of stimuli were created, each including all stimuli, which were alternated between subjects. Subjects were instructed to reduce eye-blinks and movements as far as possible, and

to restrict unavoidable movements to the breaks within the experiment. The experimental session contained five breaks of 10-sec duration.

Data recording

Electrophysiological data were collected in an electrically and acoustically shielded chamber at the EEG laboratory of the MRC Cognition and Brain Sciences Unit in Cambridge, UK. The EEG was recorded at a sampling rate of 500 Hz (0.1–30Hz band-pass filter) from 64 Ag/AgCl electrodes mounted on an electrode cap (QuickCap, Neuromedical Supplies, Sterling, VA) using SynAmps amplifiers (NeuroScan Labs, Sterling, VA). Electrodes were placed according to the extended 10/20 system. EEG data were recorded against a reference at AFz and converted off-line to average reference. The EOG was recorded bipolarly through electrodes placed above and below the left eye (vertical) and at the outer canthi (horizontal).

After the actual experiment, subjects were instructed to blink and to move their eyes to the left, right, up, and down, as indicated by symbols appearing on the computer screen. Average responses to these eye movements were used for the correction of corresponding artifacts in the EEG data [Berg and Scherg, 1994].

Data analysis

The continuously recorded neurophysiological data were divided into epochs of 1-sec length, starting 200 msec before stimulus onset. Trials with voltage variations larger than 100 μ V in at least one channel were rejected, and an eye artifact correction algorithm [Berg and Scherg, 1994] was applied. Data were band-pass filtered between 1–20 Hz. By averaging over corresponding trials, event-related potentials (ERPs) were computed for every subject, electrode, and word category. The average number of accepted trials over subjects for the conditions ARM, FACE, and LEG were 43, 41, and 41, respectively.

Source estimation

Theory

In the following, the theory of the beam-forming technique used in our analysis is outlined using basic matrix notation. Bold capital letters (like \mathbf{G}) represent matrices, and bold small letters (like \mathbf{c}) refer to column vectors. \mathbf{G}_i represents the i -th row of the matrix \mathbf{G} , \mathbf{G}_j stands for its j -th column. The superscript $'$ denotes the transposition of a vector or a matrix. In this notation, the multiplication of the row vector \mathbf{G}_i with a column vector \mathbf{d} yields a single scalar value $x = \mathbf{G}_i \mathbf{d} = \sum_j \mathbf{G}_{ij} \mathbf{d}_j$. Correspondingly, the multiplication of the row vector \mathbf{G}_i with a matrix \mathbf{L} results in a row vector whose j -th element is the product of \mathbf{G}_i with \mathbf{L}_j .

The relationship between a given source distribution inside the head and the potential measured at discrete points on the scalp surface is linear [Geselowitz, 1967], and can be formulated in matrix notation as

$$\mathbf{p} = \mathbf{Lc} \quad (1)$$

where \mathbf{p} is an $(m \times 1)$ -vector of potentials at m electrode locations, \mathbf{c} is a $(n \times 1)$ -vector containing the amplitudes of n current sources with fixed locations and orientations, and \mathbf{L} is the so-called $(m \times n)$ -“leadfield matrix” that takes into account the flow of volume currents due to volume conduction, and contains information about the geometry and conductivity distribution within the head. Each column of \mathbf{L} contains the forward solution for one of the current sources contained in the model, i.e., the potential distribution over the electrodes produced by this source alone with unit strength. The bioelectric inverse problem consists of solving this equation for \mathbf{c} when a specific \mathbf{p} is given. If $n > m$, i.e., if more sources than electrodes are taken into the model, then the source amplitudes represented by \mathbf{c} cannot be estimated independently of each other [Backus and Gilbert, 1968; Bertero et al., 1985].

However, one approach to tackle this problem is to find an $(n \times m)$ -“inverse matrix” \mathbf{G} , which multiplied with the potential vector \mathbf{p} yields an estimate $\hat{\mathbf{c}}$ of the current distribution \mathbf{c} , i.e.,

$$\hat{\mathbf{c}} = \mathbf{Gp} \quad (2)$$

Each row of \mathbf{G} (\mathbf{G}_i) is the estimator for one current source element $\hat{\mathbf{c}}_i$ in $\hat{\mathbf{c}}$. Ideally, \mathbf{G}_i should highly project on the potential distribution of the source of interest, \mathbf{L}_i , but would be orthogonal to all the others, i.e., to all \mathbf{L}_j with $j \neq i$. More formally, the values of the vector $\mathbf{i} = \mathbf{G}_i \mathbf{L}$ should be maximal at its i -th element, and vanish anywhere else; the construction of weighting coefficients \mathbf{G}_i with these properties is the core of so-called “beam-former” techniques [Baillet et al., 2001; Sekihara et al., 2002]. The idea to interpret \mathbf{G}_i as a spatial filter with band-pass properties, such that only the signal of interest is filtered out of the data and the remaining signal is suppressed, dates back to Backus and Gilbert [1968] and Capon [1969].

The vector \mathbf{r}_i describes the influence each source contained in \mathbf{c} would have on the estimate $\hat{\mathbf{c}}_i$. Therefore, it was named “resolution vector,” and the corresponding matrix $\mathbf{R} = \mathbf{GL}$ describing the resolution for all estimators contained in \mathbf{G} “resolution matrix” [Grave de Peralta et al., 1997]. The ideal choice for \mathbf{r} would be a $(1 \times n)$ -vector containing zeros everywhere except for the position of the source of interest (the i -th element), at which it should be 1. This corresponds to the i -th row of the $(n \times n)$ -identity matrix \mathbf{I}_i (which contains ones on the main diagonal, and zeros on all non-diagonal elements).

However, the construction of an optimal \mathbf{r}_i is restricted by the condition $\mathbf{r}_i = \mathbf{G}_i \mathbf{L}$, i.e., it is a linear combination of the rows of the lead-field matrix. One can only expect to optimize the behavior of the estimator \mathbf{G}_i to some degree. One straightforward choice for an optimization criterion is

$$\text{Min} (\mathbf{r} - \mathbf{I}_i)^2 \Rightarrow \text{Min}(\mathbf{G}_i \mathbf{L} - \mathbf{L}_i)^2 \quad (3)$$

which means that the least-squares difference between the ideal and the achievable resolution vector shall be minimized.

The solution to this minimization problem is unique, and yields the estimator [Menke, 1989; Grave de Peralta, 1997]

$$\mathbf{G}_i = \mathbf{L}'_i(\mathbf{L}\mathbf{L}')^{-1} \quad (4)$$

Computing such an estimator for all solution points, one obtains the inverse matrix

$$\mathbf{G} = \mathbf{L}'(\mathbf{L}\mathbf{L}')^{-1} \quad (5)$$

This corresponds to the minimum L2-norm estimator, which yields, among all possible solutions to Equation 1, the unique estimate $\hat{\mathbf{c}}$ that has minimal overall energy, i.e., $(\hat{\mathbf{c}}'\hat{\mathbf{c}})^2$ is minimal [Backus and Gilbert, 1968; Grave de Peralta, 1997]. However, estimates obtained in the framework outlined above have recently been termed “beamformer techniques” [Baillet et al., 2001; Sekihara et al., 2002].

We consider estimates obtained by this method as ideally suited for our statistical analysis, because the approach of optimized resolution vectors as described above provides us with estimates for different locations of interest that are maximally independent.

Suppression of noise

In the approach sketched above, the model contained only sources inside the brain, but no noise. The surface potential of a real recording, however, contains both the signal of interest (i.e., the signal produced by head-internal currents) as well as noise. In order to prevent that the source estimation procedure falsely produces current sources that only model the noise, but do not reflect properties of the signal of interest, a technique called “regularization” has to be applied [Bertero et al., 1988]. Regularization produces a more stable source estimate, at the cost of some spatial resolution.

If we assume that signal and noise are additive, i.e.,

$$\mathbf{d} = \mathbf{s} + \mathbf{n} \quad (6)$$

with \mathbf{d} representing the data, \mathbf{s} the signal, and \mathbf{n} the noise, then the linear estimate obtained with an inverse matrix \mathbf{G} can be analogously decomposed:

$$\mathbf{c}_i = \mathbf{G}_i\mathbf{d} = \mathbf{G}_i\mathbf{s} + \mathbf{G}_i\mathbf{n} = \mathbf{c}_{is} + \mathbf{c}_{in} \quad (7)$$

$\mathbf{C}_n = \mathbf{G}\mathbf{n}$ is the part of the estimate due to noise, and should therefore be minimized. In a least-squares framework, this can be stated as

$$\begin{aligned} \text{Min}(E[\mathbf{G}_i\mathbf{n}])^2 &\Rightarrow \text{Min}(E[(\mathbf{G}_i\mathbf{n})(\mathbf{n}'\mathbf{G}'_i)]) \Rightarrow \\ &\text{Min}(E[\mathbf{G}_i(\mathbf{nn}')\mathbf{G}'_i]) \Rightarrow \text{Min}(\mathbf{G}_i E[(\mathbf{nn}')]\mathbf{G}'_i) \end{aligned} \quad (8)$$

$E[\]$ denotes the expectation value operator. If the noise vector \mathbf{n} follows a normal distribution, i.e., if noise is spatially and temporally uncorrelated and has zero mean, this becomes [Menke, 1989; Grave de Peralta, 1997]

$$\text{Min}(\mathbf{G}_i\mathbf{G}'_i) = \sum_j \mathbf{G}_{ij}^2 \quad (9)$$

i.e., the Euclidean vector length of the estimator \mathbf{G}_i should be minimized.

This expression can be included in Equation (3), introducing the so-called “regularization parameter” λ that indicates how much weight is given to the suppression of noise:

$$\text{Min}(\mathbf{G}_i\mathbf{L} - \mathbf{I}_i)^2 + \lambda\mathbf{G}_i\mathbf{G}'_i \quad (10)$$

This yields the unique solution:

$$\mathbf{G}_i = \mathbf{L}'_i(\mathbf{L}\mathbf{L}' + \lambda\mathbf{I})^{-1} \text{ or } \mathbf{G} = \mathbf{L}'(\mathbf{L}\mathbf{L}' + \lambda\mathbf{I})^{-1} \quad (11)$$

This approach is known as Tikhonov regularization [Bertero et al., 1988]. Regularization can be interpreted as a “smoothness constraint.” The higher the noise level, the more regularization has to be applied, and the more spatial resolution has to be sacrificed to gain more stability of the solution.

Implementation

The actual implementation that was applied to individual data sets was chosen according to Hauk et al. [2002]. We used a three-dimensional source space consisting of four concentric equidistant “shells” (0.8–0.2 of electrode radius), with 1,965 current sources equally distributed over these shells. At each location, three orthogonal sources were placed. Their strengths were estimated separately, and then combined as the Euclidean vector length to yield the intensity of activity at the corresponding location.

Though it is reasonable to use a three-dimensional source space in the calculation of the solution, it has been shown that linear estimation techniques cannot reliably estimate the depth of sources unless further a priori knowledge is incorporated [Grave de Peralta et al., 1997]. It has been suggested that at least a meaningful two-dimensional projection of the source distribution can be obtained without further constraints [Hauk et al., 1999]. For our analysis, we therefore selected the uppermost shell at excentricity 0.8, containing 1,050 current sources. The corresponding resolution vectors focus mostly on superficial cortical sources in this case [Grave de Peralta et al., 1997]. Tikhonov regularization as described above was applied such that the mean residual variance over data sets was 5%.

Projection on average MRI brain

The left and right pre-auricular points and the nasion were determined for each subject and used as landmarks for both the standard electrode configuration and the seg-

mented skin surface of the average magnetic resonance image (MRI) of the Montreal Neurological Institute. These landmarks were used to co-register both modalities in the software package CURRY (Neuroscan Labs). In the spherical source model, the current sources that entered the statistical analysis were located on a sphere below the electrodes, with 80% of the electrode radius. Co-registration of the electrodes, therefore, also implied co-registration of the current sources with the average MRI. The amplitudes of these current sources were then spherically projected on the surface of the average brain.

Statistics

Because the hypothesis predicted differential activation at fronto-central cortical sites, 21 source estimates were selected that correspond to cortical areas located below the F-, FC-, and C-lines of the extended 10/20 system. These loci correspond to the cortical sites including the central and pre-central gyrus, the pre-motor areas, and adjacent frontal sites.

The source estimates for these locations entered an ANOVA as a factor TOPOGRAPHY. Data from different experimental conditions were taken as a factor WORD TYPE. One assumption underlying the ANOVA model is additivity of effects. However, the relationship between the strength of a current source and the potential distribution it produces at different recording sites on the scalp is multiplicative, i.e., if the strength of the source is multiplied by a factor s , the signal at all recording sites is also multiplied by s , and does not increase or decrease by a fixed constant for all sites [McCarthy and Wood, 1985]. A mere amplitude difference between sources might, therefore, falsely be interpreted as a topographical variation of the sources. This also holds true for linear current density estimates. Consequently, we normalized data for each subject and condition. Normalization was accomplished by subtracting the mean over data points and dividing the result by the standard deviation.

In all analyses, the Huynh-Feldt correction of degrees of freedom depending on the covariance pattern in the data was applied when appropriate. If the normalized data revealed a significant interaction WORD TYPE*TOPOGRAPHY, we performed planned comparison tests for dipole sites that were included in the ANOVA and exhibited peaks in the difference topographies.

RESULTS

Figure 3 shows maps of current estimates for the grand-mean data for relevant time points, averaged across conditions. The maps are referred to the corresponding peaks in the grand mean root-mean-square (RMS) curve calculated across all word stimuli, illustrating the time course of the overall signal strength of the event-related potential (ERPs). The curve is referred to a pre-stimulus baseline of 100 msec. It shows a steep increase in activity at approximately 100 msec after stimulus onset. The largest peak is present at 150

msec and corresponds to the N1 component of the visual ERP. Following this first peak, there is a second increase in activation starting around 210 msec and peaking at 230 msec. A third local maximum, still lower in amplitude, is apparent at 320 msec.

The maps illustrate the spatio-temporal pattern of cortical activation in the first 320 msec after visual word presentation. Around 100 msec, activity occurs in posterior brain regions, in extrastriatal visual areas that predominates in the right hemisphere. At approximately 150 msec activity is equally present in both hemispheres, but still restricted to posterior areas. Additional fronto-central brain areas become active at approximately 220 msec, where the second local maximum emerges in the RMS curve. The early spreading of activity from posterior sensory areas to frontal areas is consistent with earlier studies using intracranial recordings and MEG with distributed source analysis [Halgren et al., 1994; Marinkovic et al., 2003; Pulvermüller et al., 2003]. At the third peak of the RMS curve (~320 msec), activity in these areas has vanished. To investigate word category specific activation in the fronto-central regions, our subsequent topographical analyses focussed on the time range between 210 and 230 msec.

This choice is further supported by the time courses of the source estimates. Figure 4 presents time courses of the grand-mean source current estimates for three dipole locations at which significant differences between word categories were found (see below). These were again referred to the 100-msec baseline interval. The display of time courses for source estimates also serves as a measure for data quality: Variation in the baseline interval is low compared with peak activity after stimulus onset, indicating the source estimates are not significantly distorted by noise as an effect of regularization. Prominent peaks are visible around 200 msec (the vertical line in the plots marks the time point 220 msec).

Topographical differences between word categories were documented in the latency range 210–230 msec. Source estimates showed a significant interaction WORD TYPE*TOPOGRAPHY ($F(40,440)=1.78, P < 0.01$). The corresponding difference topographies are presented in Figure 5, projected on a standard brain surface. In the following, specific dipole locations will be referred to in the notation of the extended 10/20 system, commonly used to label electrodes.

FACE words showed more activation than LEG words in left-frontal areas ($F5, F(1,11) = 4.88, P < 0.05$), whereas the opposite was found at central sites ($Cz, F(1,11) = 8.91, P < 0.01$; $C1, F(1,11) = 8.03, P < 0.05$). This is evidence that LEG words activated dorsal central areas, whereas FACE words sparked inferior prefrontal areas. Furthermore, ARM words showed more activation than FACE words at right-central ($C4, F(1,11) = 15.51, P < 0.01$) and right-frontal ($F6, F(1,11) = 9.25, P < 0.01$) sites, and the opposite pattern was found in left pre-frontal areas ($F3, F(1,11) = 32.6, P < 0.001$). ARM words activated right frontal areas compared with

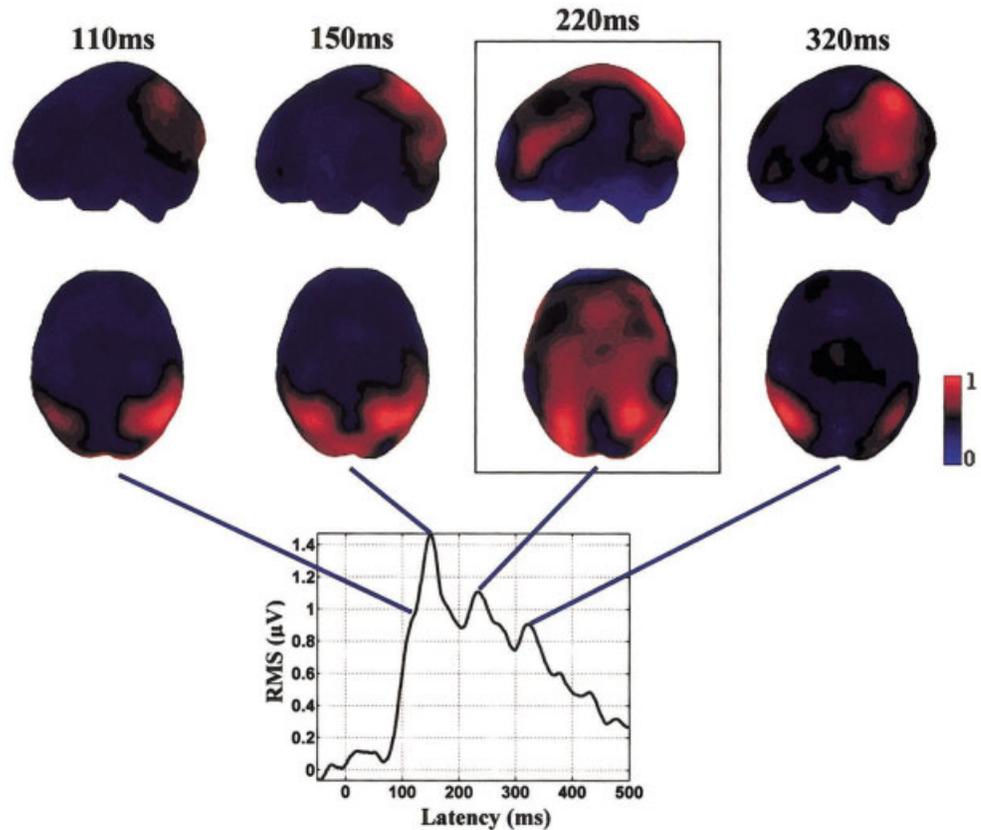


Figure 3.

Top: Current estimates of grand-mean data for selected time points illustrate the activity flow within the first few hundred milliseconds after stimulus onset. Activity in fronto-central brain areas is visible only in the time range around 220 msec. Data in the time window 210–230 msec were, therefore, submitted to a more detailed topographical analysis. **Bottom:** The overall signal strength (RMS) over time.

LEG words ($F_2, F(1,11) = 5.52, P < 0.05; F_4, F(1,11) = 15.3, P < 0.01$).

Summarizing the main features, ARM words specifically activated right-frontal areas, LEG words activated areas around the vertex, and FACE words showed activation at inferior left-frontal sites.

Though our hypotheses referred to the pattern of source distribution in the cortex rather than voltage distributions on the scalp surface, we additionally analyzed the ERP topography for the time range 210–230 msec. We selected 35 electrode locations on the F-, FC-, C-, CP-, and P-lines with the numberings 5, 3, 1, z, 2, 4, 6 according to the extended 10/20 system. A larger number of electrodes than dipoles covering a larger area of the scalp were chosen because the scalp distribution can be assumed to be more widespread than its corresponding current distribution. As for the source estimates, these electrode locations entered an ANOVA as a factor TOPOGRAPHY, together with the factor WORD TYPE. No significant interaction between these factors was revealed by this analysis.

DISCUSSION

This study investigated early electrophysiological differences between semantic categories of action words in a passive reading task. Stimuli were carefully controlled with

respect to cognitive and psycholinguistic parameters, including word frequency, length, imageability, valence, and arousal. A linear beam-forming technique was applied on ERP data sets obtained from individual subjects for specific experimental conditions, which were then submitted to statistical group analysis. Significant differences between subcategories of action words were present at approximately 220 msec.

Leg-related words activated central brain areas around the vertex, and face-related words showed more activation in inferior-frontal brain areas of the left-hemisphere. These topographical effects between 210 and 230 msec are in line with the data reported by an earlier study revealing that subcategories of action words can become neurophysiologically distinct around 200 msec after visual stimulus onset [Pulvermüller et al., 2001]. Our present study does not only replicate an early neurophysiological difference between action word types, but allows narrowing down the cortical sources that may contribute to this difference. The current estimates performed revealed that fronto-central cortical sources are differentially involved in action word processing, and that this was consistently so in a population of 12 tested subjects. Furthermore, the present results showed that the early neurophysiological word category differences arose although important psycholinguistic and cognitive factors were equated between word groups, thus excluding

Source estimate time courses

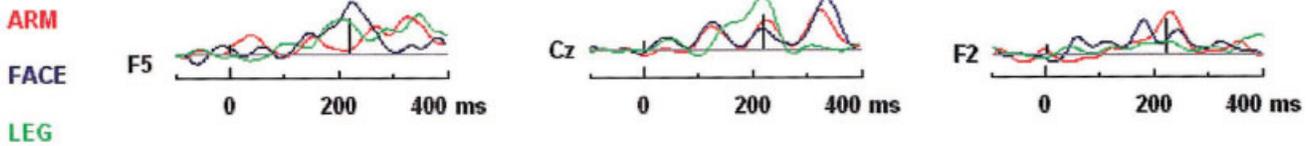


Figure 4.

Time courses of grand-mean current estimates for three selected dipole locations where differential activity between word categories is prominent. The time point 220 ms is indicated by a vertical line.

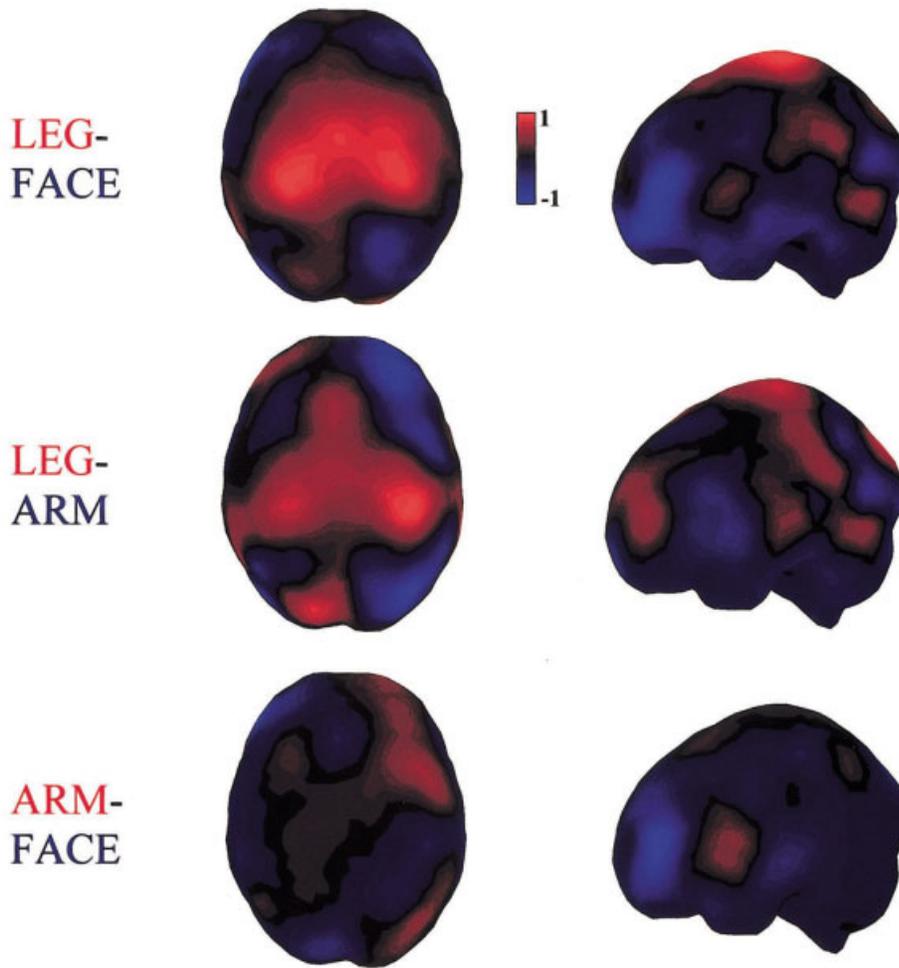


Figure 5.

Difference of grand-mean source current intensity maps for mean topographies within the time range 210–230 ms. Red colour indicates larger values at corresponding sites for subtractant, blue colour larger values for subtrahend (see labels). Maps are normalized to their respective extrema, and are presented in top view (top is front, left is left) and left view (front is left, top is up).

factors such as word frequency, length, imageability arousal, and valence as possible confounds of word category differences.

In the present data set, evoked responses with a latency of 210–230 msec reflected specific semantic processes. This is in line with earlier studies that also reported early semantic correlates in the neurophysiological brain response [Skrandies, 1998; Pulvermüller et al., 2001]. Later effects occurring in the N400 time range (300–500 msec) are usually attributed to context integration and may, therefore, reflect a later stage

in semantic and linguistic processing [Kutas and Federmeier, 2000].

As in previous studies, we found significant effects only after applying a source estimation method, but not from the “raw” event-related potentials [e.g., Pulvermüller et al., 1999, 2001]. In principle, a difference in the estimated source pattern should also be represented in the ERP data underlying the estimates. The reason for a discrepancy between these measures can be the variability in source orientation over subjects, which affects the ERP more than the source

estimate. If, for example, two ERP data sets were generated, each produced by one dipole \mathbf{d}_i at the same location, but with different orientations, their sum could be modeled by a dipole \mathbf{d} that is the vector sum of the original two dipoles, i.e., $\mathbf{d} = \mathbf{d}_1 + \mathbf{d}_2$. The amplitude $|\mathbf{d}|$ follows as $|\mathbf{d}| = \sqrt{|\mathbf{d}_1|^2 + |\mathbf{d}_2|^2 + 2|\mathbf{d}_1||\mathbf{d}_2|\cos(\alpha)}$, where α represents the angle between the dipoles. This expression is largest for $\alpha = 0$, i.e., for dipoles with the same orientation, and decreases with an increasing angle between dipoles. ERPs generated by non-parallel sources will, therefore, partially cancel each other out in the average. This problem is overcome in the source estimation technique. As described in Materials and Methods, the intensity of the source current estimates at specific locations is computed by estimating the strengths of three orthogonal dipoles at each location, and by then taking the Euclidean vector length for the resulting source, and would, therefore, yield similar values for the estimated strengths of the individual sources irrespective of their orientation. Consequently, the strengths of these estimates will be averaged properly, and not cancel each other out as in the ERP. This can explain why we found significant effects only for the latter.

Several aspects of the results obtained around 220 msec can be explained by the model of word processing outlined in the introduction. Leg-words showed more activity at central sites below Cz and C1 compared with face-words. This is consistent with the centro-dorsal location of the premotor areas involved in the execution of leg movements and, interestingly, when subjects observed actions performed with the legs [Buccino et al., 2001]. In a similar way, face-related words activated fronto-lateral sites in the left hemisphere, e.g., below FC3 (compared with arm-words) and F5 (compared with leg-words). These loci are close to the premotor cortex related to the face and arms and Broca's area anterior to the inferior primary cortex. This is again consistent with earlier fMRI work on the observation of actions performed with the mouth [Buccino et al., 2001]. The left-hemispheric comparison between leg and arm words (left diagram in the middle row of Fig. 5) suggests a similar difference between these word categories and the one seen between leg and face words. However, the specific lateral frontal activation elicited by the face words was anterior to that elicited by the arm words (see left diagram at the bottom of Fig. 5). Work on the premotor cortex in the monkey suggests that the areas where face- and arm-related neurons are found overlap to a great extent [Rizzolatti and Luppino, 2001]. We, therefore, recommend being cautious about the possible interpretation of the face- and arm-word difference. We, thus, conclude that there is a consistent difference between arm and face words (inferior frontal activation) and leg words (dorsal fronto-central activation) in the left hemisphere. A possible left-hemispheric difference between arm and face words should be further investigated in future research.

A new and unexpected finding in the present data was the strong right-prefrontal activation for arm-related words. It has recently been reported that focal lesions in the right

frontal cortex can lead to specific deficits in processing action-related words [Neininger and Pulvermüller, 2001, 2002], and the present results are consistent with the interpretation that in the healthy human brain, right hemispheric brain areas play a role in the processing of certain subtypes of action words. At present, we cannot explain why specifically the arm-related words sparked the right-frontal source. We speculate that many of the arm-words referred to complex actions (examples: to knit, to draw), and if word processing immediately activates these motor programs, some prefrontal contribution may be understandable on the basis of the well-established role of the prefrontal cortex in planning complex actions [Fuster, 1998].

The word category differences documented by the present study focusing on the frontal lobes does not exclude the possibility that additional cortical sources distinguished between the present word categories. With regard to the face words, it is remarkable that both arm and leg words elicited stronger current sources in right parieto-occipital areas (top two diagrams on the right in Fig. 5) relative to leg words, suggesting that there is an additional area in the right posterior cortex that contributes to the processing of these word categories. Although the present study did not focus on these areas, the possibility exists that the processing of action words produces differential activation outside the frontal lobes. Future studies using different imaging methods may further study this issue. The present results are consistent with models postulating that neuronal ensembles distributed over different cortical areas are the basis of word processing [Pulvermüller, 2001]. More specifically, we showed that there is significant differential fronto-central involvement in the processing of action words of different kinds. Prefrontal, premotor, and motor cortex may be sites contributing to the observed word category differences. The neurons that are differentially activated by words related to leg-, arm-, and face-actions may include mirror neurons in premotor cortex that were found to become active when specific actions are prepared for and executed, and also when the performance of these actions is perceived visually or acoustically [Rizzolatti et al., 2001; Rizzolatti and Luppino, 2001]. We propose, on the basis of the present data, that these action-related neurons are activated early when words are being processed and that they play a crucial role for identifying these words. This view is also supported by neuropsychological data about action word deficits caused by frontal lobe lesions and degeneration [Bak et al., 2001; Daniele et al., 1994; Gainotti, 2000; Neininger and Pulvermüller, 2002].

Although the present results suggest a partially "humuncular" early activation of motor areas during processing of action words, they do not allow for localizing the relevant cortical current sources with millimeter precision. One may argue that more compelling evidence could be obtained by combining ERP studies with high temporal resolution and metabolic imaging (such as functional magnetic resonance imaging, fMRI) with better spatial resolution. Due to its limited temporal resolution, however, fMRI alone cannot

distinguish between processes immediately elicited by a word and the probably strategy-dependent late processes following the initial access to the word representation. Using EEG or MEG, however, it is possible to distinguish activity in different time ranges, for example, early effects in the time range of the N1 and N2 components from late effects around 400 msec and even later. Our present results indicate that the earliest semantic differences between subcategories of action words are reflected by evoked responses around 200 msec after stimulation. At the cognitive level, this may correspond to the initial access to lexical and semantic information. This is consistent with behavioral and neurophysiological data indicating that the linguistic processes of lexical and semantic access take place near simultaneously or with only brief temporal delay within the first quarter of a second after word onset [Assadollahi and Pulvermüller, 2001; Marslen-Wilson and Tyler, 1980; Sereno et al., 1998]. In the future, MRI-constrained source modeling of EEG and MEG responses may provide a more accurate picture of the spatio-temporal activity pattern of action word processing in the human brain [Ahlfors et al., 1999; Dale et al., 2000].

ACKNOWLEDGMENTS

We are grateful to Gabriele Holz for her assistance in the selection of stimuli and data recording, to Mike Ford and Maarten van Casteren for their help in accessing relevant databases, and to Yury Shtyrov for advice and assistance in data recording and analysis.

REFERENCES

- Ahlfors SP, Simpson GV, Dale AM, Belliveau JW, Liu AK, Korvenoja A, Virtanen J, Huotilainen M, Tootell RB, Aronen HJ, Ilmoniemi RJ (1999): Spatiotemporal activity of a cortical network for processing visual motion revealed by MEG and fMRI. *J Neurophysiol* 82:2545–2555
- Assadollahi R, Pulvermüller F (2001): Neuromagnetic evidence for early access to cognitive representations. *Neuroreport* 12:207–213.
- Baayen RH, Piepenbrock R, van Rijn H (1993): The CELEX lexical database (CD-ROM). Linguistic Data Consortium, University of Pennsylvania, Philadelphia, PA.
- Backus GE, Gilbert JF (1968): The resolving power of gross earth data. *Geophys J R Astr S* 16:169–205.
- Baillet S, Mosher JC, Leahy RM (2001): Electromagnetic Brain Mapping. *IEEE Signal Proc Mag* 18:14–30.
- Bak TH, O'Donovan DG, Xuereb JH, Boniface S, Hodges JR (2001): Selective impairment of verb processing associated with pathological changes in Brodmann areas 44 and 45 in the Motor Neurone Disease-Dementia-Aphasia syndrome. *Brain* 124:103–120.
- Berg P, Scherg M (1994): A multiple source approach to the correction of eye artifacts. *Electroen Clin Neurol* 90:229–241.
- Bertero M, de Mol C, Pike ER (1985): Linear inverse problems with discrete data. I. General formulation and singular system analysis. *Inverse Probl* 1:301–330.
- Bertero M, de Mol C, Pike ER (1988): Linear inverse problems with discrete data. II. Stability and regularisation. *Inverse Probl* 4:573–594.
- Braitenberg V, Schüz A (1998): Anatomy of the cortex. Statistics and geometry. Berlin: Springer.
- Buccino G, Binkofski F, Fink GR, Fadiga L, Fogassi L, Gallese V, Seitz RJ, Zilles K, Rizzolatti G, Freund HJ (2001): Action observation activates premotor and parietal areas in a somatotopic manner: an fMRI study. *Eur J Neurosci* 13:400–404.
- Capon J (1969): High-resolution frequency wavenumber spectrum analysis. *Proc IEEE* 57:1408–1419.
- Dale AM, Sereno MI (1993): Improved localization of cortical activity by combining EEG and MEG with MRI cortical surface reconstruction: A linear approach. *J Cogn Neurosci* 5:162–176.
- Dale AM, Liu AK, Fischl BR, Buckner RL, Belliveau JW, Lewine JD, Halgren E (2000): Dynamic statistical parametric mapping: combining fMRI and MEG for high-resolution imaging of cortical activity. *Neuron* 26:55–67.
- Daniele A, Giustolisi L, Silveri MC, Colosimo C, Gainotti G (1994): Evidence for a possible neuroanatomical basis for lexical processing of nouns and verbs. *Neuropsychologia* 32:1325–1341.
- Dehaene S (1995): Electrophysiological evidence for category-specific word processing in the normal human brain. *Neuroreport* 6:2153–2157.
- Fuster JM (1995): Memory in the cerebral cortex: An empirical approach to neural networks in the human and nonhuman primate. Cambridge, MA: MIT Press.
- Fuster JM (1998): Linkage at the top. *Neuron* 21:1223–1224.
- Gainotti G (2000): What the locus of brain lesion tells us about the nature of the cognitive defect underlying category-specific disorders: a review. *Cortex* 36:539–559.
- Geselowitz DB (1967): On bioelectric potentials in an inhomogeneous volume conductor. *Biophys J* 7:1–17.
- Grave de Peralta Menendez R, Hauk O, Gonzalez Andino S, Vogt H, Michel C (1997): Linear inverse solutions with optimal resolution kernels applied to the electromagnetic tomography. *Hum Brain Mapp* 5:454–467.
- Halgren E, Baudena P, Heit G, Clarke JM, Marinkovic K, Clarke M (1994): Spatio-temporal stages in face and word processing. I. Depth-recorded potentials in the human occipital, temporal and parietal lobes. *J Physiol Paris* 88:1–50.
- Hämäläinen MS, Ilmoniemi RJ (1994): Interpreting magnetic fields of the brain: minimum norm estimates. *Med Biol Eng Comput* 32:35–42.
- Hauk O, Berg P, Wienbruch C, Rockstroh B, Elbert T (1999): The minimum norm method as an effective mapping tool for MEG analysis. In: Yoshimoto T, Kotani M, Kuriki S, Karibe H, Nakasato N, editors. Recent advances in biomagnetism (Proceedings of the 11th conference on biomagnetism). Sendai: Tohoku University Press, p 213–216.
- Hauk O, Keil A, Elbert T, Müller MM (2002): Comparison of data transformation procedures to enhance topographical accuracy in time series analysis of the human EEG. *J Neurosci Methods* 113:111–112.
- He SQ, Dum RP, Strick PL (1993): Topographic organization of corticospinal projections from the frontal lobe: motor areas on the lateral surface of the hemisphere. *J Neurosci* 13:952–980.
- Humphreys GW, Forde EME (2001): Hierarchies, similarity, and interactivity in object recognition: “Category-specific” neuropsychological deficits. *Behav Brain Sci* 24:453–509.
- Kiefer M (2001): Perceptual and semantic sources of category-specific effects: event-related potentials during picture and word categorization. *Mem Cogn* 29:100–116.
- Kiefer M, Spitzer M (2001): The limits of a distributed account of conceptual knowledge. *Trends Cogn Sci* 5:469–471.

- Kounios J, Holcomb PJ (1992): Structure and process in semantic memory: Evidence from event-related brain potentials and reaction times. *J Exp Psychol Gen* 121:459–479.
- Kutas M, Federmeier KD (2000): Electrophysiology reveals semantic memory use in language comprehension. *Trends Cogn Sci* 4:463–470.
- Marinkovic K, Dhond RP, Dale AM, Glessner M, Carr v, Halgren E (2003): Spatiotemporal dynamics of modality-specific and supramodal word processing. *Neuron* 38:487–497.
- Martin A, Wiggs CL, Ungerleider LG, Haxby JV (1996): Neural correlates of category-specific knowledge. *Nature* 379:649–652.
- Marslen-Wilson WD, Tyler LK (1980): The temporal structure of spoken language understanding. *Cognition* 8:1–71.
- McCarthy G, Wood CC (1985): Scalp distributions of event-related potentials: An ambiguity associated with analysis of variance models. *Electroen Clin Neuro* 62:203–208.
- Menke W (1989): Geophysical data analysis: discrete inverse theory. San Diego: Academic Press.
- Neininger B, Pulvermüller F (2001): The right hemisphere's role in action word processing: a double case study. *Neurocase* 7:303–317.
- Neininger B, Pulvermüller F (2003): Word-category specific deficits after lesions in the right hemisphere. *Neuropsychologia* (in press).
- Oldfield RC (1971): The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia* 9:97–113.
- Penfield W, Rasmussen T (1950): The cerebral cortex of man. New York: Macmillan.
- Perani D, Schnur T, Tettamanti M, Gorno-Tempini M, Cappa SF, Fazio F (1999): Word and picture matching: a PET study of semantic category effects. *Neuropsychologia* 37:293–306.
- Pulvermüller F (1999): Words in the brain's language. *Behav Brain Sci* 22:253–79.
- Pulvermüller F (2001): Brain reflections of words and their meaning. *Trends Cogn Sci* 5:517–524.
- Pulvermüller F, Lutzenberger W, Preissl H (1999): Nouns and verbs in the intact brain: evidence from event-related potentials and high-frequency cortical responses. *Cereb Cortex* 9:497–506.
- Pulvermüller F, Härle M, Hummel F (2001): Walking or talking? Behavioral and neurophysiological correlates of action verb processing. *Brain Lang* 78:143–168.
- Pulvermüller F, Shtyrov Y, Ilmoniemi R (2003): Spatio-temporal patterns of neural language processing: an MEG study using Minimum-Norm Current Estimates. *Neuroimage* 20:1020–1025.
- Rizzolatti G, Luppino G (2001): The cortical motor system. *Neuron* 31:889–901.
- Rizzolatti G, Fogassi L, Gallese V (2001): Neurophysiological mechanisms underlying the understanding and imitation of action. *Nat Rev Neurosci* 2:661–670.
- Sekihara K, Nagarajan SS, Poeppel D, Marantz A, Miyashita Y (2002): Application of an MEG eigenspace beamformer to reconstructing spatio-temporal activities of neural sources. *Hum Brain Mapp* 15:199–215.
- Sereno SC, Rayner K, Posner MI (1998): Establishing a time-line of word recognition: evidence from eye movement and event-related potentials. *Neuroreport* 9:2195–2200.
- Skrandies W (1998): Evoked potential correlates of semantic meaning: a brain mapping study. *Cogn Brain Res* 6:173–183.
- Warrington EK, McCarthy RA (1987): Categories of knowledge: further fractionations and an attempted integration. *Brain* 110: 1273–1296.