

Research report

# Spatio-temporal frequency characteristics of intersensory components in audiovisually evoked potentials

Oliver Werner Sakowitz<sup>a,b,\*</sup>, Rodrigo Quian Quiroga<sup>a,c</sup>, Martin Schürmann<sup>a,d</sup>, Erol Başar<sup>a,e,f</sup>

<sup>a</sup>*Institute of Physiology, Medical University Lübeck, 23538 Lübeck, Germany*

<sup>b</sup>*Department of Neurosurgery, University of Heidelberg, Im Neuenheimer Feld 400, Heidelberg D-69120, Germany*

<sup>c</sup>*Sloan-Swartz Center for Theoretical Neurobiology, California Institute of Technology, MC216-76, Pasadena, CA 91125, USA*

<sup>d</sup>*Brain Research Unit, Low Temperature Laboratory, Helsinki University of Technology, FIN-02015 HUT, Finland*

<sup>e</sup>*Department of Biophysics, Dokuz Eylül University—School of Medicine, 35340 Balcova-Izmir, Turkey*

<sup>f</sup>*TÜBITAK Brain Dynamics Research Unit, Ankara, Turkey*

Accepted 30 October 2004

Available online 9 December 2004

## Abstract

Perception of the external world is based on complex neural processes allowing for combination of sensory experiences from different modalities. Audiovisual (AV) integration is discussed in this paper on the basis of the intersensory component (IC), which is the part of the multisensory-evoked potential that is not explained by linear summation of the unisensory-evoked potentials. It was predicted that audiovisual ICs can be extracted, localized, and differentiated by means of wavelet-based frequency analysis. Healthy, right-handed subjects ( $n = 15$ ) were instructed to view and listen to presented stimuli (A: auditory; V: visual; and AV: audiovisual). Electroencephalographic data was analyzed off-line by means of wavelet transformation utilizing quadratic B-spline mother wavelets. Cross-modal interaction was investigated by subtracting wavelet responses to unimodal stimuli (A, V) alone from the wavelet responses to the combined stimuli (AV; i.e., interaction = AV – (A + V)). These difference waveforms revealed the phase-locked fraction of ICs further characterized by frequency-band and location.

Spatio-temporally distinct ICs were observed in all frequency bands [31–62 Hz (gamma), 16–31 Hz (beta), 8–16 Hz (alpha), 4–8 Hz (theta), 0.5–4 Hz band (delta)]. These were most pronounced and sustained in the theta frequency band with early (<100 ms) appearance in fronto-centro-parietal sites. In contrast, alpha-band ICs tended to appear later (>200 ms) in these locations. High-frequency (beta- and gamma-band) ICs were less organized in their spatial pattern with both early and late appearance.

ICs may reflect sensory and cognitive/integrative processes at the cortical level. In case of intersensory processing, alpha- and theta-activity appear to be spatio-temporally distinct, and could therefore participate in different stages of perception. These findings add further support to current model views of oscillatory activity in selectively distributed networks.

© 2004 Elsevier B.V. All rights reserved.

*Theme:* Neural basis of behaviour

*Topic:* Cognition

*Keywords:* ERP; Gamma; Multisensory; Oscillation; Theta; Wavelet

## 1. Introduction

The human nervous system is highly evolved in its ability to recognize, analyze, compare and react to signals

from the external world. It is rare that signals appear isolated and in one sensory modality alone. Furthermore, some signals lead to different behavioural responses when perceived contextually rather than separate. The interaction of different sensory modalities in human perception is still incompletely understood.

Unlike sequentially operating computer networks with mostly linear effects, nonlinear interactions appear in the

\* Corresponding author. Department of Neurosurgery, University of Heidelberg, Im Neuenheimer Feld 400, Heidelberg D-69120, Germany. Fax: +49 6221 56 5534.

cognitive-perceptual circuitry as can be demonstrated exemplarily. The facilitatory effect on reaction times with audiovisual stimuli, compared to auditory or visual stimulation alone, has long been known. Furthermore, concurrent visual stimulation can affect perception of acoustic stimuli and vice versa. McGurk and MacDonald [36] demonstrated the phenomenon that speech perception is affected by auditory (spoken syllables) and visual cues (dubbed lip movements) in a way that nonmatching cues produce a mismatch between the acoustic signal and the visual signal in creating a third phoneme different from the original (“McGurk effect”). Other variants of perception like synaesthesia (e.g., impression of colour when listening to words which are neutral in this respect) are puzzling examples of dynamic network properties of the brain [40]. These phenomena do suggest multisensory interaction (MSI) in the early stages of perception rather than late assembly of entirely independent sensory channels.

MSI have been tracked with modern imaging techniques like functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) [11–13,33,39,40]. Neuroanatomical methods [20] complement these findings and help to understand the underlying connectivity and where association of the senses takes place. Time-resolution of these methods, however, is limited. This is where neurophysiological methods (electroencephalography, EEG; magnetencephalography, MEG) have their greatest potential [19,22,53].

The study of the oscillatory nature of electrical brain activity has seen a renaissance in the last two decades [1,4,5]. It has been pointed out that beyond when and where brain activity occurs, how this happens may provide answers to generate a more holistic understanding of brain function. In contrast to the conventional view of ERPs as signals being added to the noisy EEG, Başar [1] pointed out that ERPs might arise from the ongoing EEG by means of a resonance process. In his concept for understanding the relation between EEG and ERP, several oscillations are occurring at the same time in a nonsynchronized way; and when a stimulus is applied, some of these frequencies can be enhanced by a resonance phenomenon. Furthermore, it was assumed that these different enhanced oscillations are related to transmitting information throughout the brain, having different “meanings” and “functions”. According to a classification of Galambos [23] event related oscillations can be evoked (originated by and time-locked to the stimulus), induced (originated by, but not time-locked to the stimulus) or emitted (originated by an internal process rather than by the external stimulus).

From “simple” primary-sensory brain functions [28,31,48] to high-level cognitive tasks involving planning, decision-making, memory-storage and -retrieval [14,21,27,30,46,51]-associated brain oscillations have been found. In neurophysiology, the underlying principles have been mostly investigated in the context of visual perception. Especially gamma-band oscillations in local and far-field potentials of

the brain have gathered attention in the field [8,10,25,38,43]. Only in a few studies on intersensory integration, frequency analysis has been applied so far [9,44,45,56].

The current paper discusses intersensory EEG activities based on the intersensory component (IC). A commonly used method to investigate MSI is to present two stimuli separately and simultaneously. The difference waveform, i.e., neural activities not explained by the arithmetic sum of uncoupled presentation, is regarded as a correlate of the surplus information that stimuli are delivered simultaneously [53]. Then, in terms of oscillatory systems analysis, the IC is the frequency component of a multisensory evoked potential unexplained by linear summation of the unisensory-evoked potentials. An easily reproducible experimental setup was chosen where simple unstructured light and sound stimuli were presented either coupled or uncoupled. No cognitive task was introduced, nor was a motor reaction necessary. We predicted that audiovisual ICs can be extracted, localized, and differentiated by means of wavelet-based frequency analysis.

## 2. Methods

### 2.1. Subjects

Electroencephalographic recordings and event-related potentials were taken from 15 right-handed subjects (8 male, 7 female, age:  $26 \pm 3$  years) without neurological deficit or reported intake of drugs known to affect the EEG. Preceding our measurements, basic personal data (name, age, handedness, past medical history, medical family history covering neurological and psychiatric aspects) was acquired during a standardized interview. Informed consent was obtained from all participants.

### 2.2. Data recording

All measurements were obtained in the facilities of the Institute of Physiology at the Medical University of Lübeck. Raw data was recorded from a Schwarzer EEG machine (Schwarzer E 1600) with Ag–AgCl disc electrodes placed on frontal, vertex, central, temporal, parietal, and occipital recording sites (F3, F4, Cz, C3, C4, T3, T4, P3, P4, O1, O2) according to the international 10–20 system. These were referenced to linked earlobe-electrodes. Anti-aliasing was achieved with a pass-band filter (0.1–70 Hz, –24 dB/octave).

A 50-Hz notch filter (6 dB/octave) was used in all experimental blocks to avoid main interferences. EEG-EP epochs (1 s pre- and 1 s post-stimulus) were digitized at a rate of 500 Hz (thus allowing safely for frequency analyses up to 250 Hz). During all sessions, paper recordings and video monitoring were used to reveal gross artifacts. Bipolar EOG (vertical–horizontal) and surface EMG of the frontalis muscle were recorded for off-line artifact rejection.

### 2.3. Experimental paradigms

Subjects rested comfortably in a soundproof investigation chamber which was dimly illuminated and well climatized. The spontaneous EEG was recorded over 2 min from all subjects with eyes open. This was used as a technical control and was used to ascertain that subjects were comfortable in the experimental surroundings. After a brief demonstration of stimulus types, stimuli were applied in sequential order with registration of 120 segments over 2 s (stimulus centered) for each condition:

- A: Sinusoidal tone (2 kHz) binaurally at 80 dB (SPL).
- V: Rectangular light-stimulus centered in the visual field at a distance of 1.5 m. This resulted in intensities exceeding surrounding illumination by approximately 5 lux (lx).
- AV: Combined stimulation, i.e., stimuli of (A) and (V) were applied simultaneously.

All interstimulus intervals were pseudo-randomized ranging from 1.0 to 3.0 s on all conditions. Accordingly, each experimental block had an approximate duration of 8 min. Prior to beginning, all subjects received demonstrations of the stimuli and were instructed to view and listen passively while maintaining focus on a marker placed in the middle of the visual stimulation field.

### 2.4. Data analysis

After visual inspection of the data, the last 30 sweeps free of artifacts were selected for each modality for offline analysis. This was done in order to include only those trials where subjects were least affected by the novelty of the situation and thus were presumably viewing (listening) passively (i.e., ignored the stimuli).

To transform EEG signals into conventionally used frequency bands we used a 5-scale wavelet decomposition, thus obtaining coefficients in the following frequency bands: 62–125 Hz, 31–62 Hz (gamma), 16–31 Hz (beta), 8–16 Hz (alpha), 4–8 Hz (theta), and the last approximation giving the activity in the 0.5–4 Hz band (delta).

The Wavelet Transform (WT [26]) gives a time–frequency representation of a signal that has two main advantages over previous methods: (a) optimal resolution in the time and frequency domains; (b) lack of the requirement of stationarity of the signal. It is defined as the convolution between the signal  $x(t)$  and the wavelet functions  $\Psi_{a,b}(t)$

$$W_{\Psi}X(a, b) = \langle x(t) | \Psi_{a,b}(t) \rangle \quad (1)$$

where  $\Psi_{a,b}(t)$  are dilated (contracted) and shifted versions of a unique wavelet function  $\Psi(t)$  and

$$\Psi_{a,b}(t) = |a|^{-1/2} \Psi\left(\frac{t-b}{a}\right) \quad (2)$$

where  $a$  and  $b$  are the scale and translation parameters, respectively.

The WT gives a decomposition of  $x(t)$  in different scales, tending to be maximum at those scales and time locations where the wavelet best resembles  $x(t)$ . Moreover, Eq. (1) can be inverted, thus giving the reconstruction of  $x(t)$ . The WT maps a signal of one independent variable  $t$  onto a function of two independent variables  $a$  and  $b$ . This procedure is redundant and inefficient for algorithm implementations. In consequence, it is more practical to define the Wavelet Transform only at discrete scales  $a$  and discrete times  $b$  by choosing the set of parameters  $\{a_j = 2^{-j}; b_{jk} = 2^{-j}k\}$ , with integers  $j$  and  $k$ . Contracted versions of the wavelet function will match the high-frequency components of the original signal and, on the other hand, the dilated versions will match low-frequency oscillations. Then, by correlating the original signal with wavelet functions of different sizes, we can obtain the details of the signal at different scales. These correlations with the different wavelet functions can be arranged in a hierarchical scheme called multiresolution decomposition [35]. The multiresolution decomposition separates the signal into ‘details’ at different scales, the remaining part being a coarser representation of the signal called ‘approximation’. Moreover, it was shown [35] that each detail ( $D_j$ ) and approximation signal ( $A_j$ ) can be obtained from the previous approximation  $A_{j-1}$  via a convolution with high-pass and low-pass filters, respectively.

For this study, we chose quadratic B-splines as mother functions due to their similarity with the evoked responses. We remark the following properties that make them optimal in signal analysis (see Ref. [15] for details): they are (anti-)symmetric and smooth; they have a nearly optimal time–frequency resolution; and they have compact support.

### 2.5. Data reduction and statistical analysis

Trend analysis was performed prior to data reduction. This was to ensure steady-state recordings within and between experimental blocks. Therefore, spontaneous EEG recordings obtained from prestimulus segments of the experimental blocks were filtered utilizing standard fast Fourier transform routines. Thus, trends within and between experimental blocks could be followed by root-mean-square (rms) values:

$$S_{\text{rms}} = \sqrt{\frac{1}{T} \int_0^T s(t)^2 dt} \quad (3)$$

with  $S_{\text{rms}}$ : root-mean-square value;  $T$ : duration of the signal;  $s(t)$ : prestimulus time-series.

For details regarding these ‘classic’ procedures in EEG signal analysis, refer to Ref. [1]. Trend analysis was performed according to Cox and Stuart [16].

Time-averages of the WT-signals were built within-subjects according to frequency band, electrode position,

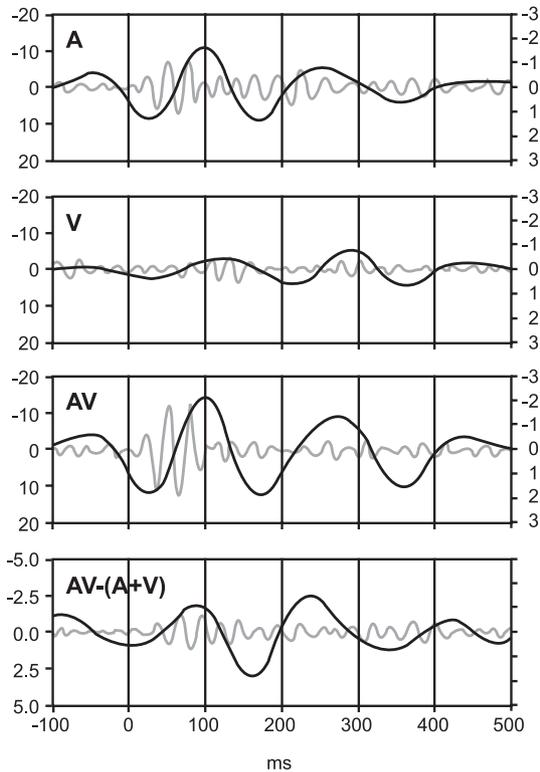


Fig. 1. [Intersensory components (ICs)]: Theta- and gamma-band wavelet-filtered evoked potentials for a typical subject (SW, measured in Cz). Along the x-axis 100 ms pre- and 500 ms post-stimulus. y-axis with arbitrary units, left for theta-band (black), right for gamma-band (grey). Negativity upwards. A: auditory-evoked potentials; V: visually evoked potentials; AV: audiovisually evoked potentials; AV – (A + V): intersensory components of audiovisually evoked potentials.

and stimulus type (A, V, AV). Additionally, difference waveforms (AV – (A + V)) were calculated (Fig. 1). They represent the fraction of the evoked potential which is attributable to the coincidence of auditory and visual

Table 1  
Subjects and predominant spontaneous EEG activity

Subject	Age	Gender	Handedness	Max. power	
				Posterior	Anterior
AS	27	m	rh	alpha	theta
BH	22	f	rh	–	alpha
CS	28	m	bh	alpha	alpha
GH	34	f	rh	alpha	alpha
GP	24	f	rh	theta, alpha	theta, beta
JR	25	f	rh	alpha	–
KB	23	f	rh	alpha	alpha
KF	26	f	rh	alpha	theta, alpha
KP	25	f	rh	alpha	theta
MJ	32	f	rh	alpha	beta
MW	24	f	rh	–	alpha
OS	24	m	rh	theta, alpha	theta, alpha
SW	24	m	rh	alpha	theta, alpha
TK	25	m	rh	alpha	alpha
WH	28	m	rh	alpha	theta, alpha

Individual characteristics of  $n = 15$  subjects. Age and handedness. rh: right-handed, bh: ambidextrous. Peaks in powerspectra of the spontaneous EEG. “Posterior” (P3, P4, O1, O2) and “anterior” (F3, F4, C3, C4) recordings.

Table 2  
Tests for trends in spontaneous EEG activity between experimental blocks

Subject	theta			alpha		
	A	V	AV	A	V	AV
AS	=	=	=	=	=	=
BH	=	=	=	+	=	=
CS	=	=	–	=	=	=
GH	=	=	=	=	=	=
GP	=	=	=	=	=	=
JR	=	=	=	=	=	=
KB	=	=	–	=	=	=
KF	=	=	=	=	=	=
KP	=	=	=	=	=	=
MJ	=	=	–	–	=	–
MW	–	=	=	=	=	=
OS	+	=	=	=	=	=
SW	=	=	=	=	=	=
TK	=	–	=	=	=	=
WH	=	–	=	=	=	=

Intraindividual significant trends of the rms values in respective experimental blocks (A: auditory; V: visual; AV: audiovisual). +: increase; –: decrease; =: no change, with  $P < 0.05$ .

stimuli. It is crucial to this method that these were not squared, and it is therefore still possible to discriminate between oscillations that are supra-additive (i.e.,  $AV > (A + V)$ ) or inverse results (i.e.,  $AV < (A + V)$ ). Direct comparison with the measured waveforms (AV, A + V) easily clarifies the nature of the difference waveform.

Then, difference waveforms were averaged across subjects ( $n = 15$ ) with 95% confidence intervals (CI) calculated and plotted. Significant ( $p < 0.05$ ) wavelets were identified whenever the envelope (CI) excluded the zero-baseline. These were the intersensory components (ICs) of the audiovisually evoked potential.

### 3. Results

Artifact-free recordings of spontaneous EEG were recorded prior to all experiments and decomposed by spectral analysis. We identified peaks in the powerspectra of posterior (P1, P2, O1, O2) and anterior (F3, F4, C3, C4) recordings.<sup>1</sup> Individual characteristics are given in Table 1. Of the 15 subjects, 11 had a posteriorly dominant alpha-rhythm, 2 had equivalent peaks in alpha and theta, and 2 had a diffuse spread of power. In anterior recordings, 6 subjects had peaks in alpha, 2 in theta, and 4 had a compound peak in alpha and theta. Peaks in theta and beta were seen in 2 subjects. One subject had predominant anterior beta-rhythm, another showed diffuse spread of power. Additionally, the rms values of prestimulus recordings were determined and

<sup>1</sup> For conventional spectral analysis, bands were defined as close as possible to the bands used with WT, i.e., as delta (1.0–3.5 Hz), theta (4.0–7.0 Hz), alpha (8.0–15.0 Hz), beta (15.0–30.0 Hz), and gamma (30.0–80.0 Hz).

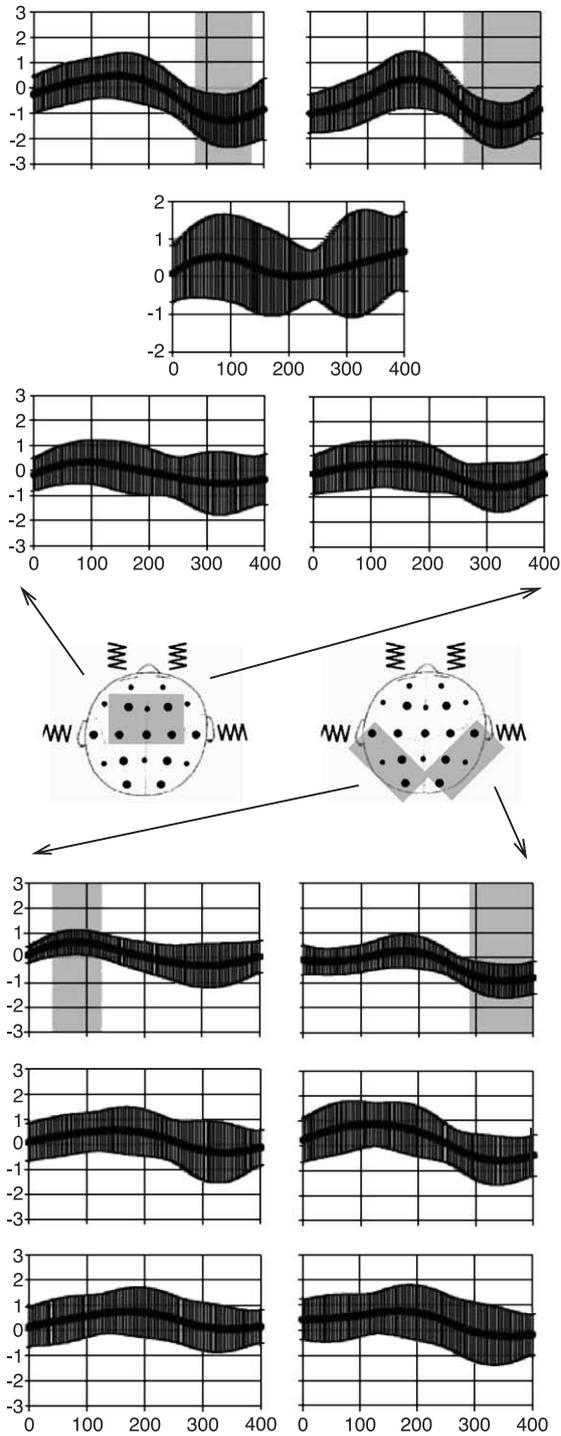


Fig. 2. [Delta-band ICs]: Grand average ( $n = 15$ ) of delta-band ICs in fronto-central and temporo-parieto-occipital recording sites (from top to bottom: F3/4, Cz, C3/4, T3/4, P3/4, O1/2). Along the x-axis, 400 ms post-stimulus. Average and 95% confidence intervals as envelope. y-axis with arbitrary units. Shaded areas highlight deviance from zero outside 95% confidence intervals.

subjected to trend analysis (Cox and Stuart). Table 2 indicates that neither in the alpha- or theta-band systematic changes within experimental blocks took place. This was also true between blocks (data not shown).

A total of 14850 artifact-free EEG-EP sweeps (15 subjects, 11 electrode sites, 3 experimental blocks, 30 sweeps per block) were analyzed according to the algorithms described in Subsection 2.4. The audiovisual ICs for each frequency band and electrode position were determined and graphically presented. Only ICs significantly deviant from 0 (i.e., outside the 95% CI) were highlighted. These were

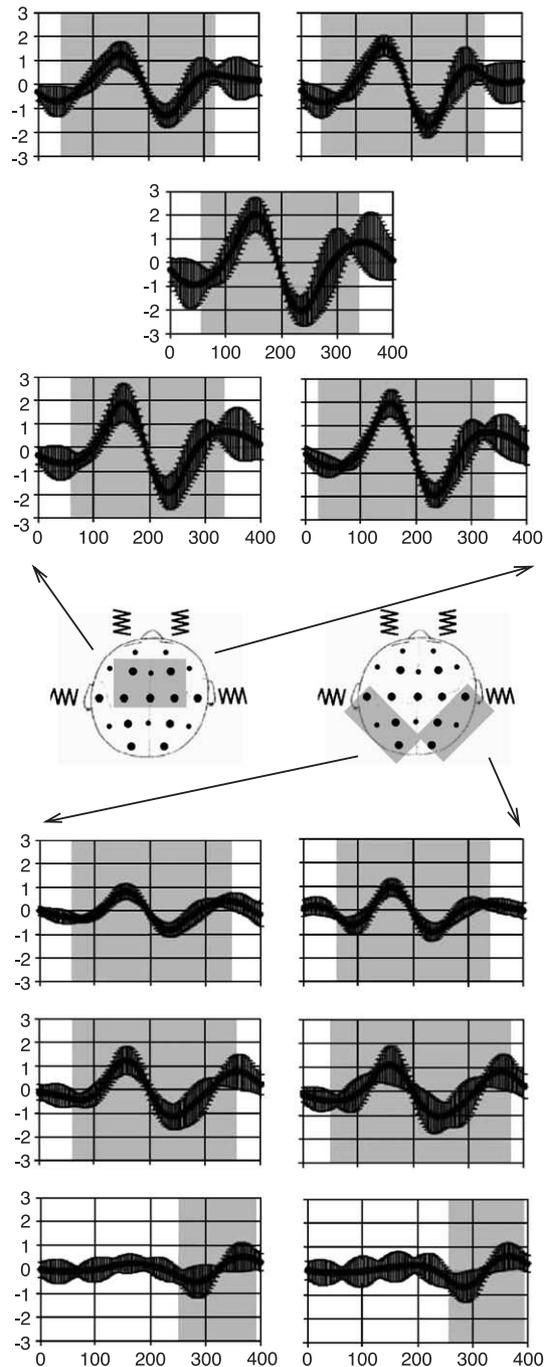


Fig. 3. [Theta-band ICs]: Grand average ( $n = 15$ ) of theta-band ICs. Along the x-axis 400 ms post-stimulus. Average and 95% confidence intervals as envelope. Y-axis with arbitrary units. Shaded areas highlight deviance from zero outside 95% confidence intervals.

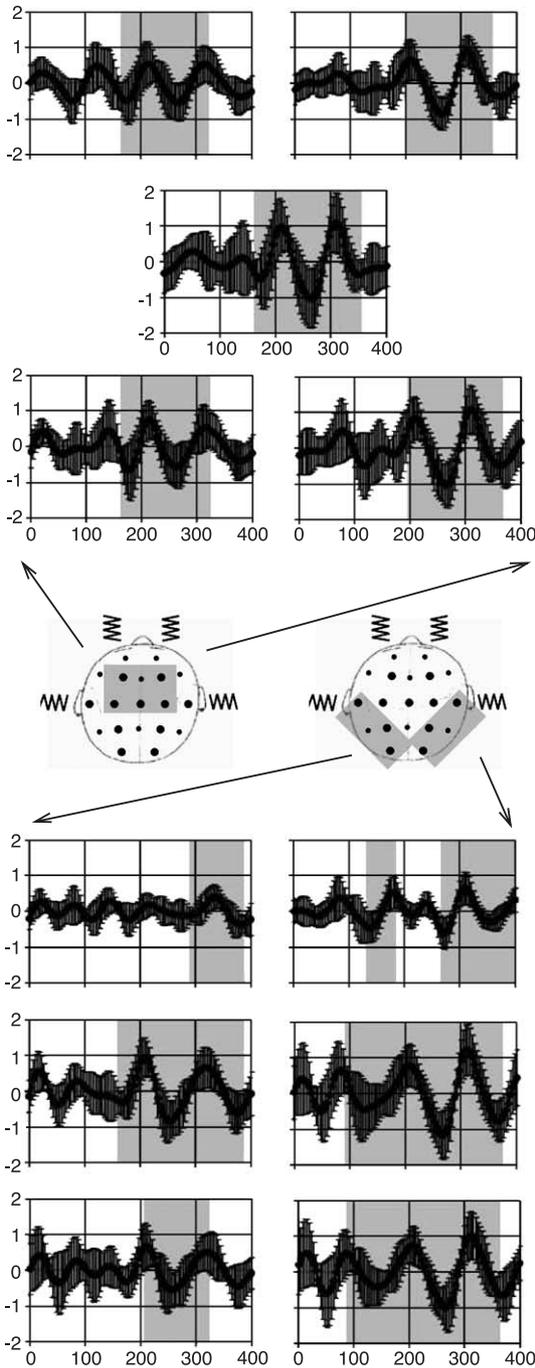


Fig. 4. [Alpha-band ICs]: Grand average ( $n = 15$ ) of alpha-band ICs. Along the  $x$ -axis, 400 ms post-stimulus. Average and 95% confidence intervals as envelope.  $y$ -axis with arbitrary units. Shaded areas highlight deviance from zero outside 95% confidence intervals.

compared with auditory, visually and audiovisually evoked potentials. All ICs were supra-additive in nature (cf. Subsection 2.5).

In the delta-range, late ( $\approx 300$  ms) ICs were observed bifrontally (F3, F4) and right-temporally (T4; Fig. 2). Significance was reached in the negative deflection only. Except for a positivity in T3 ( $\approx 50$ – $100$  ms), early occurring intersensory components were not seen.

Theta-range ICs appear uniformly over fronto-centro-parietal (F3, F4, C3, C4, C4, P3, P4) recording sites, less-pronounced bitemporally (T3, T4; Fig. 3). These ICs are mainly characterized by a positive wave 150–160 ms after stimulation and a negative wave at 220–230 ms after stimulation. Overall, ICs start early ( $<100$  ms) and are significantly sustained until 300–330 ms after stimulation.

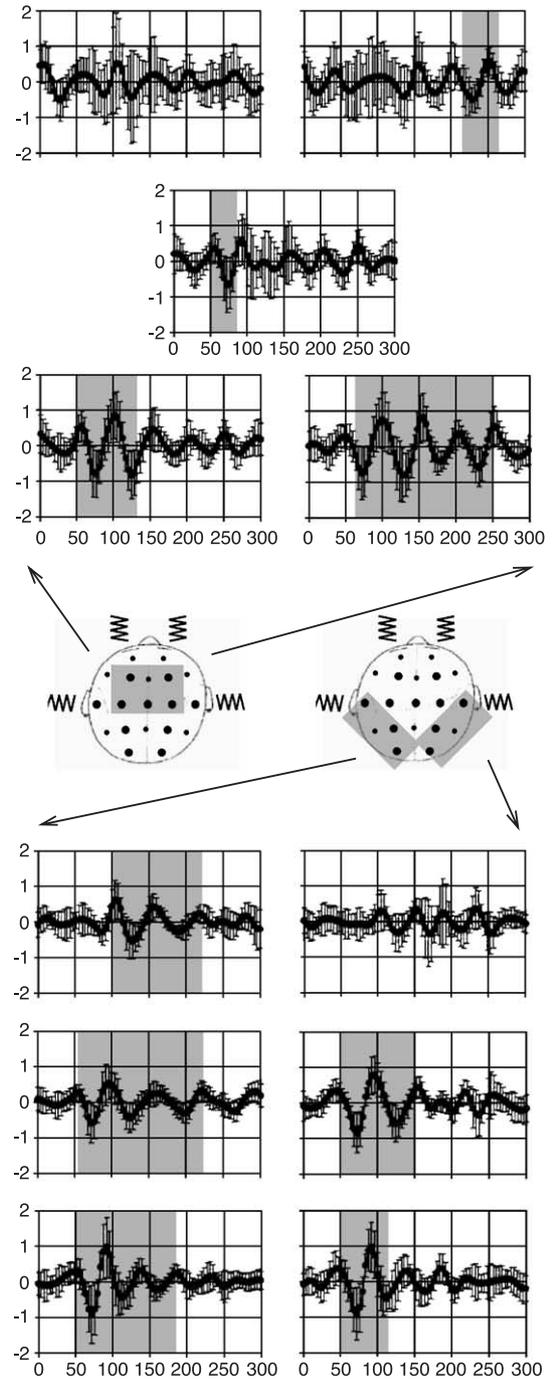


Fig. 5. [Beta-band ICs]: Grand average ( $n = 15$ ) of beta-band ICs. Along the  $x$ -axis, 300 ms post-stimulus. Average and 95% confidence intervals as envelope.  $y$ -axis with arbitrary units. Shaded areas highlight deviance from zero outside 95% confidence intervals.

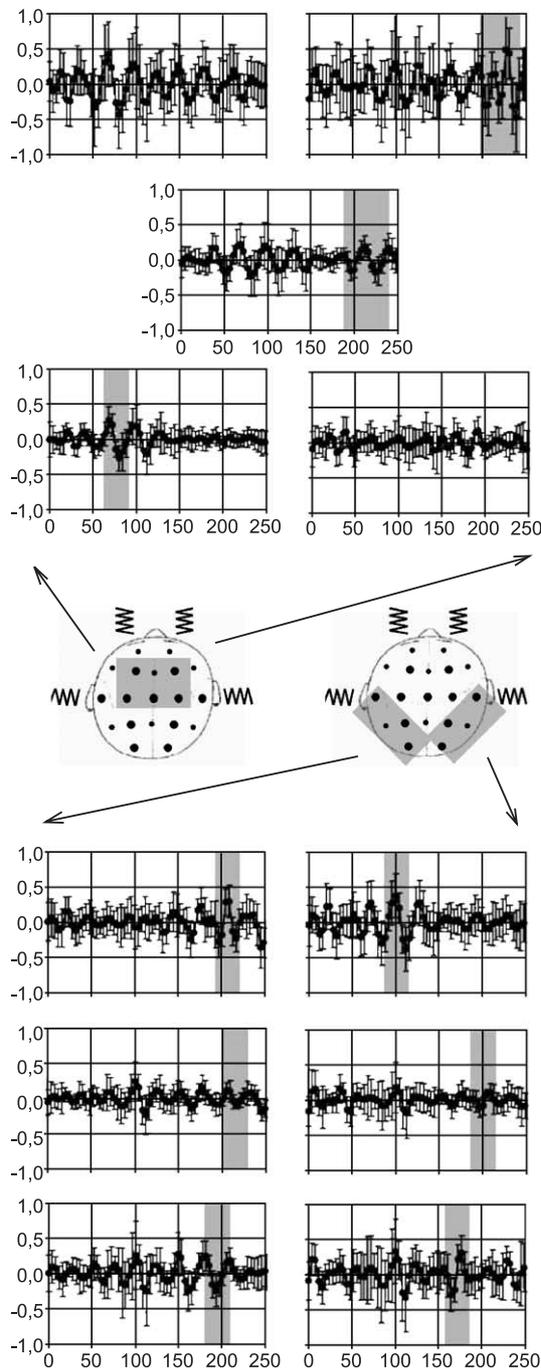


Fig. 6. [Gamma-band ICs]: Grand average ( $n = 15$ ) of gamma-band ICs. Along the  $x$ -axis, 250 ms post-stimulus. Average and 95% confidence intervals as envelope.  $y$ -axis with arbitrary units. Shaded areas highlight deviance from zero outside 95% confidence intervals.

In occipital recordings, only late, sustained theta-range IC appear from  $\approx 260$  to 380 ms.

Significant alpha-range ICs were observed in all recording sites (Fig. 4). Similar features, i.e., a prominent alpha-oscillation from 180–200 ms to 350–400 ms, were seen in fronto-central (F3, F4, Cz, C3, C4) and left parieto-occipital (P3, O1) recordings. Similar alpha-band ICs were seen right temporo-parieto-occipally (T4, P4, O2) with an early IC

around 100 ms merging into/or starting it. Bitemporally, ICs were only weakly expressed and late in appearance ( $\approx 280$ –300 ms).

Beta-band ICs were among the earliest observed ICs. These were centro-parieto-occipally (Cz, C3, C4, T3, P3, P4, O1, O2) located and appeared as early as 50 ms after stimulus presentation (Fig. 5). In the left central (F4) and parieto-occipital recordings, these appeared prolonged up to 180–250 ms. Left temporally (T3) significant ICs were observed from 100 to 220 ms after stimulus. Frontally, only a late (220–260 ms) IC was seen on the right side (F3).

Intersensory gamma-responses were seen both early (75–100 ms) and late (175–250 ms) after stimulation (Fig. 6). They appeared spatio-temporally less-organized than ICs in other frequency ranges. In right temporal (T4) and left central (C3) locations, significance was reached for early ICs. Regarding late-appearing ICs, significance was reached for fronto-central (F4, Cz) and temporo-parieto-occipital (T3, P3, P4, O1, O2) recordings.

#### 4. Discussion

Wavelet-based analysis of audiovisually evoked potentials revealed ICs in all frequency bands with distinct temporo-spatial characteristics. Table 3 summarizes these findings. The advantages of WT procedures in the analysis of evoked potentials in general and the modifications used here specifically have been discussed previously [42,45]. For the propaedeutics of ERP-frequency analysis, we refer to [1,4,5]. Substance of the current approach were evoked EEG-activities phase-locked to the onset of stimulation and associated with “passive” audiovisual MSI.

Even with “passive” listening/viewing, attentional effects might remain and arguably differ between unisensory and bisensory stimulation [28]. We tried to control these by (i) presenting test stimuli before each experimental block, (ii) using balanced interstimulus intervals, and (iii) choosing the last third of recordings for all stimuli. The last third of the experiment supposedly contains those trials where the subject is most familiar with the stimuli, thereby minimizing

Table 3  
Spatio-temporal characteristics of audiovisual ICs

	Latency		
	<100 ms	100–200 ms	>200 ms
frontal			beta
fronto-central	<i>theta</i>	alpha, gamma	
central	<i>beta, gamma</i>		
fronto-temporal	<i>theta</i>		delta
temporal	gamma	gamma	alpha
temporo-parietal	<i>theta</i>		
parieto-occipital	<i>alpha, beta</i>	gamma	
occipital			theta, alpha

Overview of significant ICs listed according to latency (early: <100 ms, intermediate: 100–200ms, late: >200ms) and location. Prolonged activity (spanning more than one latency category) in italics.

novelty and arousal. This advantage outweighed the disadvantage of fatigue.

It is crucial to point out that evoked EEG changes were nonsustained and the underlying EEG itself was stable within and between experimental blocks. Therefore, status changes related to arousal or fatigue are unlikely to account for the results. Then, the hypothetical explanation of the intersensory response is that EEG activities synchronize, possibly transmitting information that two sensations are manifestations of the same process.

Oscillatory activities measurable in the time-course of the EEG have been candidates for information processing in the CNS. These rhythmicities being present in (sub)cortical structures and systems seem to be linked to functional states of the brain which correlate with behavioural measures.

Both theta- and delta-responses have been correlated with the P300 response [7,17,50]. Bifrontal and left temporal negativities, however, were observed in the delta-range ICs. Given that these occurred around 300 ms following audiovisual stimulation, this may still indicate an effect on the P3a response seen with novel stimuli and cognitive processing of these. Since auditory and visual processes share at least parts of the “P300 system”, it would be conceivable that multisensory stimulation results in a less than additive P3a component in audiovisually evoked potentials. Therefore, caution is advised that an algorithm that subtracts a slow (anticipatory) component twice (A+V) from (AV) could lead to an erroneous introduction of a slow IC [53]. Accordingly, we aimed to suppress novelty- and anticipation-related effects using a passive listening/viewing paradigm. Indeed, late-appearing slow rhythmic potentials do not appear to be significantly associated with MSI here.

The most robust findings were observed in theta-band ICs. These appear early (<100 ms after stimulation) fronto-centro-parietal (less-pronounced bitemporal) and are significantly sustained up to 300–330 ms following stimulation. In occipital recordings, these were small and late in appearance.

The bisensory theta-response was described earlier and discussed in context with the selectively distributed theta-response system [3–5,44]. Coherent and noncoherent theta-range oscillations of human EEG have been repeatedly found associated with increased “cognitive load” [14,21,27,30,46,51]. We assume that the theta component of evoked potentials might reflect the responsiveness of brain areas involved in global associative processing (e.g., cortico-cortical MSI, possibly involving the limbic system).

Ubiquitous alpha-ICs were seen, first appearing in a right temporo-parieto-occipital distribution, then affecting both sides fronto-centrally. Alpha-ICs were among the longest-lasting and pronounced responses. In contrast to theta-band ICs, only the late or sustained (i.e., >200 ms after stimulation) components were observed fronto-centrally. It has been previously discussed that distinct frequency-bands are attributable to various brain functions. The early appearing alpha-frequency band activities have thereby

been found predominantly with sensory tasks adjacent to primary–sensory cortices [6,41,48]. In contrast to theta-band ICs, the alpha-band ICs of evoked potentials might reflect the responsiveness of brain areas involved in local associative processing (e.g., thalamo-cortical MSI, possibly with a two-phase recruitment).

In summary, alpha- and theta-range ICs were more pronounced than ICs of higher frequencies. Theta-band ICs tended to occur earlier and more anteriorly located than alpha-band ICs.

The various combinations of different time windows and topographies lead to, in fact, different “alphas” and “thetas”; these different oscillations, in turn, might represent different functions [4,5]. This has led to the idea that functions like sensory processing and cognitive processing might also be differentially represented by “preferred frequencies” [3,6,48].

In the model view of Klimesch [29], a more anteriorly organized (limbic) theta-system, functionally linked to tasks involving episodic memory, coexists with a posterior (thalamic) alpha-system modulated by long term memory tasks. Oscillations in these frequency bands possibly provide the basis for encoding, accessing, and retrieving cortical codes that are stored in form of widely distributed but intensively interconnected cell assemblies. Similarly, as outlined above, theta-responses have been found upon tasks with a cognitive load. This is accompanied by evoked-alpha desynchronization, with the lower alpha desynchronization being related to active attention and upper alpha desynchronization to semantic memory [29,30].

In previous reports, coherent and noncoherent gamma-responses in the human EEG were found with sensory as well as cognitive functions [28,45,52,55]. When acoustic stimuli are coupled to visual stimuli, additional acoustic stimuli have been associated with the experience of an “illusionary” flash [49]. Then, interestingly, the intersensory illusionary flash is accompanied by significantly higher oscillatory and induced gamma band responses [9]. In this study, higher-frequency ICs appeared spatio-temporally less organized. Gamma-ICs occurred diffusely spread over fronto-central and temporo-parieto-occipital scalp locations following audiovisual stimulation.

Both beta- and gamma-ICs were observed as early as 50 ms following stimulation. In comparison, this early intersensory activity was predominantly expressed in the beta-range. Cortical responses to visual stimuli are most robust  $\approx$  100 ms after light stimuli (P100) although they may appear around 50 ms after stimulation, as for example, in the C1 component of pattern-onset VEPs. Audiovisual interactions appear to take place early in time also (this study and Refs. [24,37]). In central and parieto-occipital recordings, pronounced ICs were observed. Recent neurophysiological findings underscore that first steps of multisensory convergence happen at the time or prior to cortical sensory processing. Indeed, a common finding of behavioral studies is that objects characterized by redundant multisensory cues are identified more rapidly than the same

objects presented in either unimodal condition. The suggested modes of action are both feedback and feed-forward processes. This assumption is supported by, e.g., the analysis of the laminar profile of converging inputs in primate multisensory cortex [47]. It is left to speculation whether early appearing ICs could represent the preattentive processing stages that are necessary to combine synchronous sensory input to a unique gestalt.

Two particular arguments against the theory of oscillatory brain dynamics have to be discussed. General concern is raised by the observation of synchronous states associated with nonfunctional behaviour (e.g., seizures, slow-wave sleep, comatose states). On the other hand, various oscillations in different frequency bands, individually and concurrently, have been described in association with simple sensory stimulation, but they similarly appear with high-level cognitive tasks. Can there be an encoding principle through synchronous brain activities, if these are multiple and not strictly assigned to the very precise operations of the brain?

As previously formulated by Tononi and Edelman, it may be hypothesized that there are more requirements for conscious brain functioning than the ability to generate EEG synchrony. Sufficient dynamical complexity of brain activity, both temporally and spatially, seems to be one more necessary condition [54].

In analogy to the generation of language, Başar [2] compared oscillatory frequency bands to letters of the alphabet that form syllables, words and sentences. Hence, not a single oscillatory activity but moreover an ensemble of oscillations would bind locally active brain areas and generate percepts (or even allow cognitive processes through long-range synchronization) [2,31]. Accordingly, neural assemblies would replace the neuron in the description of complex brain functions. Vice versa, oscillatory activities (event-related, induced, or spontaneous) would govern the most general transfer functions in the brain (with alpha, beta, gamma, delta, theta, etc., EEG oscillations as demonstrated here using the wavelet approach). Generally, the ability to oscillate in different frequency ranges would be a neuronal “atomar” property [18,25,31,32,34]. In this model, however, selectively distributed oscillatory neural populations behave with “molecular properties”. These oscillatory networks are activated upon sensory stimulation or event-related tasks by manifestation of (partial) synchrony, enhancements, blocking or desynchronization of oscillations depending on the nature of the sensation or event and, accordingly, depending on the function performed. These selectively distributed networks would then be the flexible operators (building blocks) of general brain functions including communication, association and data retrieval [4,5].

## 5. Conclusion

Intersensory components (IC) are part of the multisensory evoked potential and not explained by linear

summation of the unisensory evoked potentials. These ICs can be extracted, localized, and differentiated by means of wavelet-based frequency analysis. ICs may reflect sensory and basic integrative processes at the cortical level.

Spatio-temporally distinct ICs were observed in all frequency bands. Theta-band ICs are the governing manifestation of oscillatory EEG activity elicited by coupled and simultaneous audiovisual stimulation. They appear early in time, are sustained, and are fronto-centro-parietally-organized. In contrast, alpha-band ICs appear later in time (>200 ms after stimulation). Of early occurrence (as soon as 50 ms after stimulation) and less organized (adjacent to multiple cortical areas) were ICs in higher-frequency bands.

In case of intersensory processing, alpha- and theta-activity appear to be spatio-temporally distinct, and could therefore participate in different stages of perception. These findings support current model views of oscillatory activity in selectively distributed networks. With an ensemble of spatio-temporally distinct network, activities like these large-scale synchronization could take place maintaining complexity at the same time.

## 6. Disclaimer

All data recordings were obtained at the Institute of Physiology/Medical University of Lübeck (Germany). Parts of this paper were presented orally at the 11th World Congress of Psychophysiology (Montreal, August 2002) organized by the International Organization of Psychophysiology associated with the United Nations (New York).

## References

- [1] E. Başar, EEG Brain Dynamics. Relation Between EEG and Brain Evoked Potentials, Elsevier, 1980.
- [2] E. Başar, Thoughts on brain's internal codes, in: E. Başar (Ed.), Dynamics of Sensory and Cognitive Processing by the Brain, Springer, Berlin Heidelberg, 1988, pp. 381–384.
- [3] E. Başar, Brain natural frequencies are causal factors for resonances and induced rhythms, in: E. Başar, T. Bullock (Eds.), Induced Rhythms in the Brain, Birkhäuser, Boston, 1992, pp. 170–179.
- [4] E. Başar, Brain Function and Oscillations: I. Brain Oscillations: Principles and Approaches, Springer, Berlin Heidelberg, 1998.
- [5] E. Başar, Brain Function and Oscillations: II. Integrative Brain Function: Neuro-physiology and Cognitive Processes, Springer, Berlin, 1999.
- [6] E. Başar, M. Schürmann, Functional aspects of evoked alpha and theta responses in humans and cats: occipital recordings in “cross modality” experiments, *Biol. Cybern.* 72 (1994) 175–183.
- [7] C. Başar-Eroğlu, E. Başar, T. Demiralp, M. Schürmann, P300-response: possible psychophysiological correlates in delta and theta frequency channels. A review, *Int. J. Psychophysiol.* 13 (1992) 161–179.
- [8] C. Başar-Eroğlu, D. Strüber, P. Kruse, E. Başar, M. Stadler, Frontal gamma-band enhancement during multistable visual perception, *Int. J. Psychophysiol.* 24 (1996) 113–125.

- [9] J. Bhattacharya, L. Shams, S. Shimojo, Sound-induced illusory flash perception: role of gamma band responses, *NeuroReport* 13 (2002) 1727–1730.
- [10] S. Bressler, R. Coppola, R. Nakamura, Episodic multiregional coherence at multiple frequencies during visual task performance, *Nature* 366 (1993) 153–156.
- [11] G. Calvert, M. Brammer, E. Bullmore, R. Campbell, S. Iversen, A. David, Response amplification in sensory-specific cortices during crossmodal binding., *NeuroReport* 10 (1999) 2619–2623.
- [12] G. Calvert, R. Campbell, M. Brammer, Evidence from functional magnetic resonance imaging of crossmodal binding in the human heteromodal cortex, *Curr. Biol.* 10 (2000) 649–657.
- [13] G. Calvert, P. Hansen, S. Iversen, M. Brammer, Detection of audio-visual integration sites in humans by application of electrophysiological criteria to the BOLD effect, *Neuroimage* 14 (2001) 427–438.
- [14] J. Caplan, J. Madsen, A. Schulze-Bonhage, R. Aschenbrenner-Scheibe, E. Newman, M. Kahana, Human theta oscillations related to sensorimotor integration and spatial learning, *J. Neurosci.* 23 (2003) 4726–4736.
- [15] C. Chui, *An Introduction to Wavelets*, Academic Press, San Diego, 1992.
- [16] D. Cox, A. Stuart, Some quick tests for trend in location and dispersion, *Biometrika* 42 (1955) 80–95.
- [17] T. Demiralp, A. Ademoglu, M. Comerchero, J. Polich, Wavelet analysis of P3a and P3b, *Brain Topogr.* 13 (2001) 251–267.
- [18] H. Dinse, K. Krüger, H. Mallot, J. Best, Temporal structure of cortical information processing: cortical architecture, oscillations, and non-separability of spatio-temporal receptive field organization, in: J. Krüger (Ed.), *Neuronal Cooperativity Models and Experiments*, Springer, 1991, pp. 20–24.
- [19] M. Eimer, Crossmodal links in spatial attention between vision, audition, and touch: evidence from event-related brain potentials, *Neuropsychologia* 39 (2001) 1292–1303.
- [20] A. Falchier, S. Clavagnier, P. Barone, H. Kennedy, Anatomical evidence of multimodal integration in primate striate cortex, *J. Neurosci.* 22 (2002) 5749–5759.
- [21] J. Fell, P. Klaver, H. Elfadil, C. Schaller, C. Elger, G. Fernandez, Rhinal-hippocampal theta coherence during declarative memory formation: interaction with gamma synchronization? *Eur. J. Neurosci.* 17 (2003) 1082–1088.
- [22] A. Fort, C. Delpeuch, J. Pernier, M. Giard, Early auditory–visual interactions in human cortex during nonredundant target identification, *Brain Res. Cogn. Brain Res.* 14 (2002) 20–30.
- [23] R. Galambos, A comparison of certain gamma band (40-Hz) brain rhythms in cat and man, in: E. Başar, T. Bullock (Eds.), *Induced Rhythms in the Brain*, Birkhäuser, Boston, 1992, pp. 201–216.
- [24] M. Giard, F. Peronnet, Auditory–visual integration during multimodal object recognition in humans: a behavioral and electrophysiological study, *J. Cogn. Neurosci.* 11 (1999) 473–490.
- [25] C. Gray, P. König, A. Engel, W. Singer, Oscillatory responses in cat visual cortex exhibit inter-columnar synchronization which reflects global stimulus properties, *Nature* 338 (1989) 335–337.
- [26] A. Grossmann, J. Morlet, Decomposition of Hardy functions into square inte-grable wavelets of constant shape, *SIAM J. Math. Anal.* 15 (1984) 723–736.
- [27] M. Kahana, R. Sekuler, J. Caplan, M. Kirschen, J. Madsen, Human theta oscillations exhibit task dependence during virtual maze navigation, *Nature* 399 (1999) 781–784.
- [28] S. Karakaş, E. Başar, Early gamma response is sensory in origin. A conclusion based on cross comparison of results from multiple experimental paradigms, *Int. J. Psychophysiol.* 31 (1998) 13–31.
- [29] W. Klimesch, Memory processes, brain oscillations and EEG synchronization, *Int. J. Psychophysiol.* 24 (1996) 61–100.
- [30] W. Klimesch, M. Doppelmayr, H. Schimke, B. Ripper, Theta synchronization and alpha desynchronization in a memory task, *Psychophysiology* 34 (1997) 169–176.
- [31] P. König, A. Engel, W. Singer, Relation between oscillatory activity and long-range synchronization in cat visual cortex, *Proc. Natl. Acad. Sci. U. S. A.* 92 (1995) 290–294.
- [32] K. Kopecz, G. Schöner, F. Spengler, H.R. Dinse, Dynamic properties of cortical evoked (10 Hz) oscillations: theory and experiment, *Biol. Cybern.* 69 (1993) 463–473.
- [33] P. Laurienti, J. Burdette, M. Wallace, Y. Yen, A. Field, B. Stein, Deactivation of sensory-specific cortex by cross-modal stimuli, *J. Cogn. Neurosci.* 14 (2002) 420–429.
- [34] R. Llinás, The intrinsic electrophysiological properties of mammalian neurons: insights into central nervous system function, *Science* 242 (1988) 1654–1664.
- [35] S. Mallat, A theory for multiresolution signal decomposition: the wavelet representation, *IEEE Trans. Pattern Anal. Mach. Intell.* 2 (1989) 674–693.
- [36] H. McGurk, J. MacDonald, Hearing lips and seeing voices, *Nature* 264 (1976) 746–748.
- [37] S. Molholm, W. Ritter, M. Murray, D. Javitt, C. Schroeder, J. Foxe, Multisensory auditory–visual interactions during early sensory processing in humans: a high-density electrical mapping study, *Brain Res. Cogn. Brain Res.* 14 (2002) 115–128.
- [38] M. Müller, J. Bosch, T. Elbert, A. Kreiter, M. Sosa, P. Sosa, B. Rockstroh, Visually induced gamma-band responses in human electroencephalographic activity—a link to animal studies, *Exp. Brain Res.* 112 (1996) 96–102.
- [39] I. Olson, J. Gatenby, J. Gore, A comparison of bound and unbound audio-visual information processing in the human cerebral cortex, *Brain Res. Cogn. Brain Res.* 14 (2002) 129–138.
- [40] E. Paulesu, J. Harrison, S. Baron-Cohen, J. Watson, L. Goldstein, J. Heather, R. Frackowiak, C. Frith, The physiology of coloured hearing. A PET activation study of colour-word synaesthesia, *Brain* 118 (1995) 661–676.
- [41] R. Quian Quiroga, M. Schürmann, Functions and sources of event-related EEG alpha oscillations studied with the wavelet transform, *Clin. Neurophysiol.* 110 (1999) 643–654.
- [42] R. Quian Quiroga, O. Sakowitz, E. Başar, M. Schürmann, Wavelet transform in the analysis of the frequency composition of evoked potentials, *Brain Res. Brain Res. Protoc.* 8 (2001) 16–24.
- [43] E. Rodriguez, N. George, J. Lachaux, J. Martinerie, B. Renault, F. Varela, Perception’s shadow: long-distance synchronization of human brain activity, *Nature* 397 (1999) 430–433.
- [44] O. Sakowitz, M. Schürmann, E. Başar, Oscillatory frontal theta responses are increased upon bisensory stimulation, *Clin. Neurophysiol.* 111 (2000) 884–893.
- [45] O. Sakowitz, R. Quian Quiroga, M. Schürmann, E. Başar, Bisensory stimulation increases gamma-responses over multiple cortical regions, *Brain Res. Cogn. Brain Res.* 11 (2001) 267–279.
- [46] J. Sarnthein, H. Petsche, P. Rappelsberger, G. Shaw, A. von Stein, Synchronization between prefrontal and posterior association cortex during human working memory, *Proc. Natl. Acad. Sci. U. S. A.* 95 (1998) 7092–7096.
- [47] C. Schroeder, J. Foxe, The timing and laminar profile of converging inputs to multisensory areas of the macaque neocortex, *Brain Res. Cogn. Brain Res.* 14 (2002) 187–198.
- [48] M. Schürmann, E. Başar, Topography of alpha and theta oscillatory responses upon auditory and visual stimuli in humans, *Biol. Cybern.* 72 (1994) 161–174.
- [49] L. Shams, Y. Kamitani, S. Shimojo, Illusions. What you see is what you hear, *Nature* 408 (2000) 788.
- [50] K. Spencer, J. Polich, Poststimulus EEG spectral analysis and P300: attention, task, and probability, *Psychophysiology* 36 (1999) 220–232.

- [51] H. Stampfer, E. Başar, Does frequency analysis lead to better understanding of human event related potentials? *Int. J. Neurosci.* 26 (1985) 181–196.
- [52] C. Tallon-Baudry, O. Bertrand, C. Delpuech, J. Pernier, Stimulus specificity of phase-locked and non-phase-locked 40 Hz visual responses in human, *J. Neurosci.* 16 (1996) 4240–4249.
- [53] W. Teder-Salejarvi, J. McDonald, F. di Russo, S. Hillyard, An analysis of audio-visual crossmodal integration by means of event-related potential (ERP) recordings, *Brain Res. Cogn. Brain Res.* 14 (2002) 106–114.
- [54] G. Tononi, G. Edelman, Consciousness and complexity, *Science* 282 (1998) 1846–1851.
- [55] A. von Stein, P. Rappelsberger, J. Sarnthein, H. Petsche, Synchronization between temporal and parietal cortex during multimodal object processing in man, *Cereb. Cortex* 9 (1999) 137–150.
- [56] J. Yordanova, V. Kolev, O. Rosso, M. Schürmann, O. Sakowitz, M. Ozgören, E. Başar, Wavelet entropy analysis of event-related potentials indicates modality-independent theta dominance, *J. Neurosci. Methods* 117 (2002) 99–109.