Using multimodal frequency tagging for BCI

I.H.S Mischner, R.S. Schaefer, C. Gielen and P. Desain

Cognitive Artificial Intelligence group

Nijmegen Institute for Cognition and Information

Radboud University Nijmegen

November 14, 2007

ABSTRACT

Stimuli that are presented with a constant frequency elicit responses in the brain that oscillate at that same frequency, also known as steady-state responses (SSRs). SSRs promise to be useful brain patterns for brain computer interfaces (BCI), because their amplitudes can be modulated by attention. However, signal-to-noise ratios are relatively low, and stronger brain signals are needed to increase performances. Previous research on crossmodal amplification has demonstrated that stimulation in one modality can amplify brain signals elicited by stimulation in another modality, thereby yielding stronger signals. To investigate the possibilities of crossmodal amplification for use in BCI-systems, an offline EEG experiment based on a frequency-tagging paradigm was carried out, with stimuli presented in three modality condition: an auditory, tactile and audio-tactile condition. Frequency tags were 20 and 28 Hz. Stimuli were either presented to one side of the body (passive perception condition) or to both sides, and the participant had to focus attention on one side of his body (selective attention condition). To ensure attention, small time interruptions (phase shifts) were added to the streams, and the participant was instructed to count the number of interruptions at the attended side. Evoked power at the tagging frequencies was then used to make a comparison between the different modalities. The results do not support the added value of combining auditory and tactile stimulation when making use of the effect of attention on the steady-state response to generate brain signals that may drive a BCI-system.

INTRODUCTION

Brain-Computer Interface (BCI) research aims to develop a system through which a user can drive a device using covert action only, in other words, by making use of the measurable brain activity produced by mental actions alone. Although a variety of applications can be thought of for such a system, the most obvious use is for people who have no other way of interacting with their surroundings. The most salient example of this situation is the progressed phase in Amyotrophic Lateral Sclerosis (ALS), in which efferent peripheral motor neurons die and render the patient completely paralyzed, while the central nervous system is still relatively unaffected (although for a review of cognitive functioning of ALS patients, see Rippon et al., 2006). The output device of the BCI can vary from a language interface for communication to the navigation of a wheelchair or remote controls for the living environment, such as a light switches or a television.

While these BCI-systems are still being developed, and a diverse range of systems is emerging, some aspects of these systems are the same for all of them. The basic elements and steps that are needed in a BCI-system are the user and the mental task, the measurement of brain activity, the preprocessing of this brain activity, the extraction of useful features from this preprocessed brain activity, the classification of the brain activity, and the output or feedback. Each of these elements or procedures may be different for different systems, thereby producing various results. Up till now, a variety of mental tasks have been designed and investigated, which will be discussed more elaborately below, often yielding a two-class problem or two tasks to choose from. However, sometimes it is possible to choose between more classes, allowing a multidimensional output. Different ways of measuring brain activity have been used, both invasive (i.e. implanted electrodes, either in or on the cortex) and non-invasive (i.e. measuring brain activity from outside of the head, as in electro-encephalography (EEG) or functional magnetic resonance imaging (fMRI)). Considering the risks of brain surgery and the logistics of using an fMRI-scanner, EEG, which picks up electrical signals from the brain by electrodes placed on the scalp, is a method much preferred in this field and focused on exclusively here. Different ways of analysis in preprocessing have their effect on both feature extraction and classification of new brain data. When the measurements are classified into categories, they are translated into commands to control the external device. Although some good results have been produced by allowing the system to learn and adapt to the user, it is important to realize the brain is not consistent but plastic. Thus, if the system keeps adapting to the brain which keeps adapting, it is unlikely to find stability.

Generally, the success of a BCI system is expressed in bit-rate. The most commonly used definitions of bit-rate incorporate a measure of accuracy of the classifier, the number of classes, and the time needed to make a classification (for an overview of different definitions of bit-rate, see Kronegg, Voloshynovskiy and Pun, 2005). Although the systems that are currently being developed provide a solid proof of concept, they are generally still too slow or too inconsistent to use in real-life situations. In order to develop a system that will meet the needs of users in terms of time needed to train for them, as well as in speed and accuracy, much research is still needed. In the research presented here, a new paradigm and alternative ideas for a BCI system will be described. First, however, some existing paradigms will be discussed.

Previous BCI research

One of the big challenges in designing a BCI is to identify robust patterns in brain activity that can easily be detected. Slow cortical potentials, sensorimotor-rhythms and the P300 potential are the brain activity patterns that are most frequently used to drive a BCI (Wolpaw, Birbaumer, McFarland, Pfurtscheller, and Vaughan, 2002). Slow cortical potentials (SCPs) are slow voltage changes in the EEG that occur over several seconds, and reflect the amount of activity of the underlying cortical areas. Negative SCPs are associated with a high cortical activation, while positive SCPs are associated with a reduction in brain activity. Birbaumer and colleagues showed that some people are able to learn to control these potentials, and can thereby operate a spelling device (Birbaumer et al., 1999). However, training to learn to control SCPs takes a lot of time and is very demanding, and thus not ideal for a patient user group.

Sensorimotor-rhythms are patterns in the brain that are evoked by both performing movements as well as imaging movements (Pfurtscheller and Da Silva, 1999). The synchronization and desynchronization in the beta and gamma band that arise by imagining movements can be used to move a cursor to a target on a computer screen (Pfurtscheller, Neuper, Schlogl, and Lugger, 1998). However, long immobility and degeneration of pyramidal cells in motor cortex, as is the case in ALS, may influence the imagined movement-related brain activity that can be classified. As of yet, it is unclear what the effect of extended immobility is on the processing of the primary motor cortex.

The P300 potential is a positive peak in the EEG around 300 ms that is elicited by a rare event, in this case the flickering of a visual stimulus. This response is only generated when the stimulus is attended to, and Farwell and Donchin (1988) showed that the P300-like component evoked by focusing attention to one of 36 infrequent flickering letters or punctuation marks can be used to communicate that desired character.

Steady-state responses

However, another very promising though less investigated brain activity pattern is the steady-state evoked potential (SSEP). Stimuli that are presented with a constant frequency elicit responses in the brain that oscillate at the same frequency. Two examples of SSEPs are the steady-state somatosensory evoked potential (SSSEP) and the auditory steady-state response (ASSR). The SSSEP is evoked by repeated pressure against the skin, e.g. pins vibrating against a finger, and is generated in the primary somatosensory cortex (Nangini, Ross, Tam, and Graham, 2006). The rate of the vibration will determine the frequency of the response, and will thereby serve as a frequency tag/signature in the EEG. Stimulation frequencies near 21 Hz elicit the strongest responses (Tobimatsu, Zhang and Kato, 1999). The ASSR is generated in the auditory cortex, and can be elicited by an auditory stimulus such as a sine tone, of which the amplitude is modulated (Roß, Borgmann, Draganova, Roberts and Pantev, 2000). Again, the amplitude modulation (AM) frequency serves as a frequency tag in the EEG. In the auditory domain, optimal modulation frequencies lay in the 40 Hz range (Pastor, Artieda, Arbizu, Marti-Climent, Peñuelas and Masdeu, 2002). The amplitude of the ASSR can be increased by the inclusion of higher harmonics in the carrier wave (thereby approximating a sawtooth; Stürzebecher, Cebulla and Pschirrer, 2001), by modulating the amplitude of the carrier wave with a block-modulator instead of a sine-modulator (John, Dimitrijevic and Picton, 2002), and by modulating both the amplitude and the frequency of the carrier wave with the same frequency (John, Dimitrijevic, van Roon and Picton, 2001). A study in which different modulation depths were used showed that the ASSR response increases with increasing modulation depth. However, there is a saturation effect for depths larger than 0.5 (Lins, Picton and Picton, 1995).

Although an SSEP can also be elicited by visual stimuli (e.g. visual flicker), that response will not be discussed here. In the context of BCI, visual perception is not independent of muscle activity in the same way that auditory and tactile perception are.

Steady-state responses and selective attention as a paradigm for BCI

Different studies have been done to investigate the effect of attention on steady-state responses. Ross and colleagues constructed an MEG experiment in which auditory (AM-tones) and visual stimuli (pictures on a screen, though not presented with a constant frequency and thereby not eliciting a SSEP) were presented at the same time, and participants were instructed to focus attention to one modality while ignoring the other modality. Results showed that the ASSR was largely enhanced when the auditory stimuli were attended to (Ross, Picton, Herdman, Hillyard, and Pantev, 2004).

Giabbiconi and coworkers demonstrated that also the SSSEP can be modified by attention (Giabbiconi, Dancer, Zopf, Gruber, and Müller, 2004). In their experiment, both index fingers were stimulated with vibrating pins and participants had to attend to one finger while ignoring the other. The amplitude of the SSSEP elicited by the stimulus presented at the attended finger was significantly larger than the one elicited by the stimulus at the unattended finger. The biggest attention effects were found at frontal and fronto-central electrode locations contralateral to the attended finger.

The knowledge that SSEPs can be modulated by attention yields specific possibilities when creating a mental task that can be used to drive a BCI (Desain, Hupse, Kallenberg, de Kruif, and Schaefer, 2006). The user can focus his or her attention to a stimulus of choice, thereby selecting a corresponding command to be carried out by the output device. The direction of the users attention can be inferred by classification from the EEG and used accordingly. Selective attention is a mental task that the brain is especially good at, and something we have to do continually in order to prevent information overload. Attending to a stimulus thus is relatively easy and does not require any training. There are only a few studies done in which attention is used to drive a BCI. One of these is performed by the group of Müller-Putz in Graz. Their investigation of a BCI system based on SSSEPs and attention showed that participants were able to modulate their SSSEPs, and that it was possible to classify the direction of their attention (left-right) with an accuracy of 70-80% after 5 days of training with online feedback (Müller-Putz, Scherer, Neuper, and Pfurtscheller, 2006).

Although not directly based on the ASSR, but making use of attention-modulated auditory responses, Hill and coworkers describe a BCI system with an accuracy of 63-97% (Hill, Lal, Bierig, Birbaumer, and Scholkopf , 2004). Here, two trains of auditory events were presented on the left and right side, and by averaging the auditory event-related responses over time, the attended stream could be detected.

However, there is a lot of variety in the performance of people and the low signal-to-noise ratio remains a big problem. To improve classification rates, stronger signals are needed. One possible way to achieve this is to use multimodal stimuli instead of unimodal stimuli.

Multimodal amplification

All objects around us consist of several characteristics that can be experienced by different senses. For example, by touching an object, sensory signals are sent to sensory-specific brain regions specialized in that modality, in this case to the somatosensory cortex, and an image is created of how the object feels. In the same way, visual and auditory information related to the object are processed by the visual and auditory cortices, respectively. However, to form a coherent percept of the stimulus and to know that all these sensations belong to the same object, the responses to the different modalities need to be integrated by the brain. First it was thought that this integration was done by hierarchical sensory convergence (Macaluso, 2006). Stimulation in two different modalities elicit responses in both modality-specific areas. However, these areas process the sensory inputs independently of each other, as separate modules. These sensory specific areas then project anatomically to common multisensory areas in parietal, frontal and posterior temporal cortex (higher associative areas), where neurons respond to stimuli in more than one modality. The converging feed-forward projections coming from sensory-specific areas will allow interactions between signals from different senses in these higher areas.

However, various studies (e.g. lesion studies, illusion studies and multimodal enhancement studies) show that sensory modalities do not work as separate modules, but there are interactions between the different sensory modalities (Shimojo and Shams, 2001). There are two hypotheses how information concerning one modality can reach brain regions dedicated to a different modality (Macaluso, 2006). The first is that there are top-down feedback influences, so back projections from higher associative areas to unimodal areas (modulatory feedback). The second considers direct feed-forward influences: there are direct connections/projections between the different unimodal areas. These two hypotheses are not mutually exclusive. Top-down influences might follow some automatic interactions based on direct connections. A schematic overview of these models is shown in figure 1.

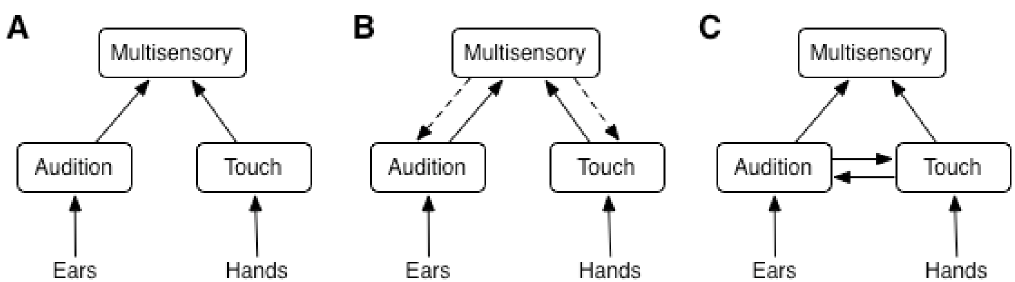

Figure 1. Different models of multimodal integration. A: hierarchical sensory convergence. B: Top-down feedback influences. C: Direct feed-forward influences.

All these direct and indirect connections between different modality-specific brain regions lead to interactions and modifications of signals in unimodal areas. One of these interactions is crossmodal amplification: stimulation in one modality amplifies brain signals elicited by stimulation in another modality. Crossmodal amplification suggests that multimodal stimuli can provide stronger brain signals than unimodal stimuli, that might lead to better classification due to a higher signal-to-noise ratio. Calvert and colleagues did a study in which they investigated the interactive effects between audio and vision (Calvert, Brammer, Bullmore, Campbell, Iversen and David, 1999).

Participants listened to a female voice enumerating numbers between 1 and 10, while looking at a female face. In one condition the face was static (unimodal speech), while in the other condition the lips of the face moved congruently with the spoken words (bimodal speech). Enhanced activity in both the auditory and the visual cortex was present during the bimodal speech perception (seeing helps hearing). Macaluso and coworkers investigated the effect of simultaneous visuo-tactile stimulation on the activity of the visual cortex, and showed that tactile stimulation enhanced the response in the visual cortex when the tactile stimulus was presented at the same side as the visual stimulus, compared to when the tactile stimulus was presented at the contralateral side, or when the visual stimulus was presented alone (Macaluso, Frith, and Driver, 2000).

To investigate the possibilities of crossmodal amplification for use in a BCI-system, an offline EEG experiment based on a frequency-tagging paradigm was carried out, with stimuli that were presented in three modality conditions: an auditory, tactile and audio-tactile condition. The rationale behind this was that if a user learns to perceive a frequency tagged stimulus presented in two modalities as one percept, the crossmodal amplification may yield a more robust signal than if it is perceived in only one modality. Based on the findings reported by Tobimatsu et al. (1999), two AM frequencies were selected to have no overlap in higher harmonics and were in the range of optimal response for tactile stimulation, namely 20 and 28 Hz. Because the optimal modulation frequencies for tactile and auditory stimuli differ (20 and 40 Hz respectively), a compromise had to be made between these two ranges. The auditory modality is very sensitive for temporal patterns, and has therefore no problems processing and distinguishing higher frequencies. However, the somatosensory modality is less sensitive for timing, and a modulation frequency of 40 Hz tended to be too fast for tactile stimulation, especially to detect small interruptions in time which was crucial in this experiment. To maximize the ease of separation of the two streams, they were spatially separated in presentation to different sides of the body. The auditory stimuli were also made to separate maximally through their sound characteristics. This was done by using carrier frequencies that are not harmonically related, using an approximation of a sawtooth wave instead of a sine, and by modulating the carrier frequency as well. To compare between passive perception and active selective attention, stimuli were either presented to only one side of the body (i.e. one ear/hand; the perception condition), or to both sides of the body (i.e. both ears/hands; the selective attention condition). To ensure attention, a small number of deviants were added to the streams. The instruction to count these deviants was meant to increase motivation as well. Although different types of deviants have been piloted, previous work on the analysis of phase in this paradigm suggested the use of a phase jump as a deviant. No extensive training was used, besides a short introduction and a few practice trials.

By presenting stimuli with a constant frequency, we expect to measure a steady-state response in the brain that oscillates at that same frequency. When a second stream is added and presented with a different frequency to the other side of the body, we hypothesize that stimuli presented at the attended body side will elicit larger steady-state responses than stimuli presented at the unattended side. Based on crossmodal amplification, we further hypothesize that audio-tactile stimulation will elicit larger steady-state responses in the brain than audio or tactile stimulation alone, both in the passive perception condition and in the selective attention condition.

METHODS

Participants

One male subject, age 25, participated in this experiment. He had no previous experience with the experiment. The subject was free of any neurological disorders. He had normal vision and normal hearing.

Stimuli

Auditory stimuli: The auditory stimuli consisted of amplitude-modulated tones (AM tones) presented to the left and right ear trough a passive headphone (Beyerdynamic DT48). Carrier-frequencies were 420 Hz for the left ear and 980 Hz for the right ear, plus their second, third and fourth harmonic. An equal loudness filter was applied to the stimuli to equalize the subjective loudness of the two streams.

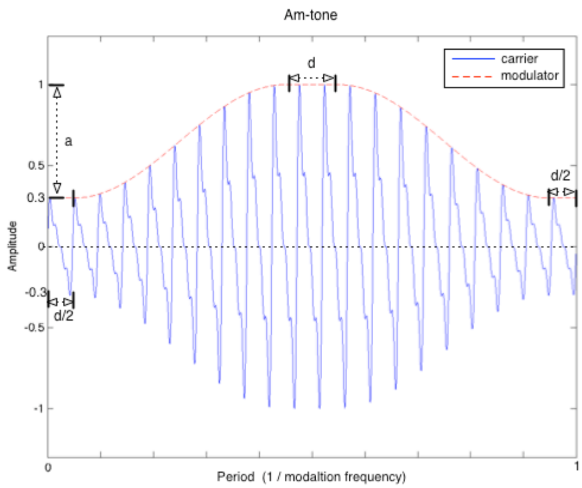

Figure 2. Carrier wave (blue) and amplitude modulator (red). Modulation depth (a) is 0.7, cosine section (d) is 0.1.

The waveform of the modulator was a sine wave with short cosine sections (d = 0.1) inserted at maxima and minima, yielding a wave between a sine and a block (see Fig 2). Modulation frequencies were 20 and 28 Hz, and the modulation depth (a) was 0.7. Next to the amplitude, the frequency of the carrier wave was modulated as well, thereby giving a reverberating effect. For this frequency modulation (FM), a quarter of a semitone was used. Figure 3A shows the auditory stimulus.

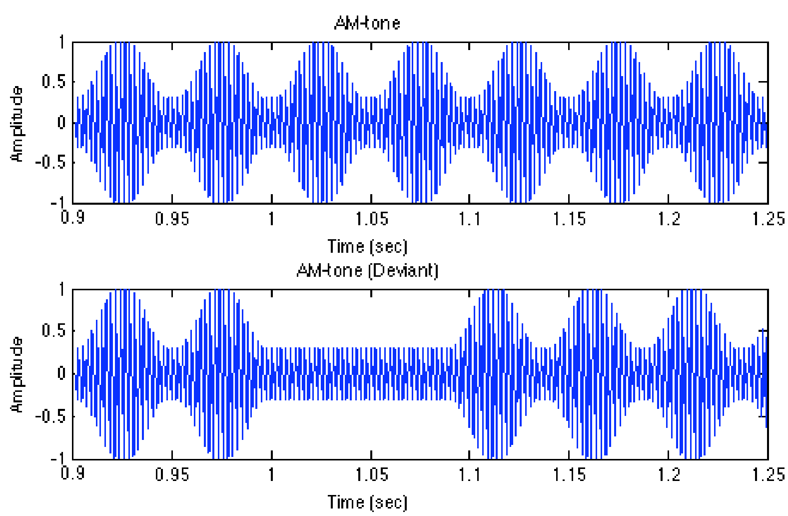

Figure 3. A: Amplitude-modulated tone with a carrier-frequency of 420 Hz and a modulation frequency of 20 Hz. B: Auditory deviant with a phase-shift of 1.75 period at 1 second after pattern onset.

Tactile stimuli: Two piezo-electrical Braille stimulators were used to stimulate four fingers of both hands. These Braille stimulators were fitted into four stacked discs, forming a cylinder that can comfortably be fitted into a hand, comparable to a drinking cup (see Fig 4). Each disc had two rows of four pins, that can be raised and lowered together or in (braille) patterns. The discs can be rotated independently to accommodate for different hand sizes and place the pins underneath the fingertips, the part of the finger with the biggest representation on the somatosensory cortex. For this experiment, all pins on one cylinder were raised and lowered in synchrony for each hand, with vibration frequencies of 20 and 28 Hz.

Figure 4. Piezo-electrical Braille stimulator.

Audio-tactile stimuli: Both auditory and tactile stimuli were presented simultaneously. Stimuli presented at the same body side had identical stimulation frequencies (20 or 28 Hz) and were in phase.

Stimulation periods of 2.5 seconds were generated, in which the stimulus was modulated with either 20 or 28 Hz, further referred to as a stimulus pattern. Next to the normal patterns, deviants were created for both auditory and tactile stimuli, which had small time interruptions, i.e. a phase-shift of 1.75 and 0.25 periods, 1 second after pattern onset and at the end of the pattern respectively. Figure 3B shows an auditory deviant.

All stimuli were generated as MIDI in Matlab 7.2 with a sample rate of 44.1 kHz, and were presented through Logic Express 7.0.1, a MIDI sequencer.

Experimental task

The task for the participant was to direct his attention to one side of his body, and count the number of deviants presented at that side. Stimuli were presented in one of three modalities: in the auditory, tactile or audio-tactile modality. There were two stimulation conditions: a passive perception condition in which only one side of the body was stimulated (i.e. one hand and/or ear), and a selective attention condition in which both body sides were stimulated simultaneously and the participant was instructed to selectively attend to stimuli presented at one side of his body while ignoring the stimuli on the other side.

In half of the trials the left side of the body was stimulated or, in case of the selective attention task, had to be attended, whereas in the other half of the trials the right side of the body was stimulated/attended. Trials were presented in random order.

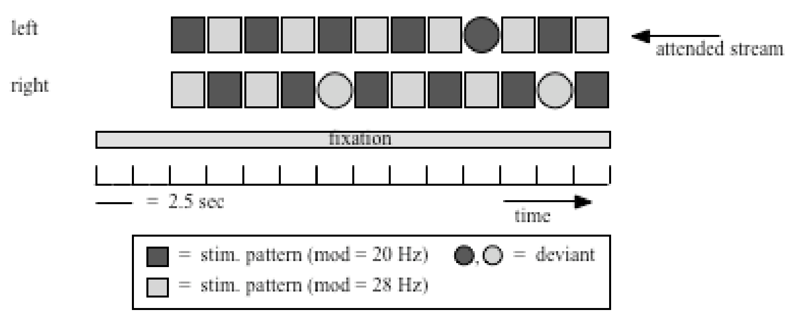

Figure 5. Outline of a trial in the selective attention condition.

Figure 5 depicts the outline of a trial in the selective attention condition. Every trial started with a baseline period of 5 seconds, in which the participant solely had to fixate at a cross presented on the screen. One leg of the fixation cross was green to indicate which side of the body had to be attended. After this baseline period, stimulation started and lasted for 30 seconds. Each 2.5 seconds the stimulation frequency alternated between 20 and 28 Hz. In all the trials of the selective attention condition and in 60% of the trials in the perception condition deviants were occasionally presented at the attended or unattended side. At the end of the trial the participant had to indicate how many deviants he had detected at his attended side by pressing a button, choosing between 0, 1 or 2 deviants. In case the answer was unknown, the subject could indicate this through a “haven’t-paid-attention-button”. Deviants were added to make sure the participant was directing his attention, and feedback about performance was given to keep motivation high. During the whole stimulation period the fixation cross remained on the screen. The participant himself could initiate each following trial by pressing a button, thus offering the opportunity to blink, relax, stretch and make other movements between trials and minimize these during data collection. The outline of a perception trial is the same as the selective attention trial (as in Fig 5), but without the second stimulation stream. A series of four practice trials was added before each block of a new condition, so the participant could familiarize himself with the task.

The whole experiment included 12 blocks: 2 stimulation conditions x 3 modalities x 2 blocks per modality. Each block consisted of 20 trials, which contained 12 stimulation patterns each, resulting in 240 patterns per block, and 120 patterns per stimulation frequency. In the perception condition, 10 of these patterns were deviants and not used for further analysis. In the selective attention condition, 14 patterns were deviants and excluded from further analysis. Each trial had a duration of 44 seconds, which made the length of a block about 15 minutes.

Because of the length of the experiment and to ensure attention, the measurements were spread over three successive days. The routine of each day was the same (two blocks of the perception task, followed by two blocks of the selective attention task), only the modality in which the stimuli were presented differed. The participant performed the task in the auditory modality, the tactile modality, and the audio-tactile modality (in that order). During the tactile and the audio-tactile condition the Braille stimulators were wrapped in isolating material to suppress the noise generated by the vibrating pins. During the tactile condition the participant wore earplugs as well.

Data acquisition/Electrophysiological (EEG) recording

The EEG-signal was recorded from 256 locations on the scalp, using an elastic cap with active electrodes (BioSemi Active 2 System). All electrode offsets were kept below a threshold of 25 mV. Vertical eye movements and blinks were monitored by electrodes placed above and below the right eye, and horizontal eye movements by electrodes placed lateral to both eyes. The 256 EEG channels were digitized with a sample rate of 512 Hz and stored on disc for off-line analysis.

Data analysis

All data analysis was done using Matlab. To remove impurities from the data, the raw EEG signals were preprocessed. First, the average value of all channels was computed and taken as a reference. Then, bad channels were detected visually and removed from the data. The data of the remaining channels were spatially down sampled using linear interpolation, resulting in 64 virtual channels with locations according to the international 10-20 electrode system. After preprocessing, the EEG data was cut into data segments of 2 seconds, starting 500 ms after stimulus onset or frequency switch and lasting until the end of the stimulation pattern. A Fast Fourier Transform (FFT) with a Hanning window of 2 seconds was applied to each data segment individually, to compute the power and phase of the induced activity. Then, event related potentials (ERPs) were computed by averaging the EEG signals per condition, and were transformed to the frequency domain by performing a FFT with a Hanning window of 2 seconds. Power increases at different frequencies were obtained by subtracting the spectra of contrasting attention conditions. Table 1 shows these different contrasts.

Task	Condition 1: Attention left	Condition 2: Attention right
Perception	L20-r00	l00-R28
	L28-r00	l00-R20
Selective Attention	L20-r28	l20-R28
	L28-r20	l28-R20

Table 1. Compared attention conditions. Letters indicate the stimulation side (l=left, r=right), and the numbers attached to them specify which tagging frequency is presented at that side. The capitals indicate which side is attended to. No stimulation is denoted by 00.

For example, in the selective attention task, the condition L20-r28 is contrasted with the l20-R28 condition. In both conditions the left side of the body is stimulated with 20 Hz and the right side by 28 Hz. However, in the first condition the attention is focused on the left side of the body, whereas in the second condition the attention is on the right side. The power-difference between these two conditions expresses the power gain by attention. The power gain at the tagging frequencies were then used to make a comparison between the different modalities. Interesting comparisons were audio-tactile vs. auditory, and audio-tactile vs. tactile. The significance of these differences was obtained by performing a randomization test in combination with a Z-test: all raw data in the time domain belonging to the two contrasting modalities were put together, and randomly reordered in two classes. The average signal (ERP) of each class was calculated, and transformed to the frequency domain. The difference in power at each tagging frequency was taken as an estimate of the difference between the two modalities at that frequency. This procedure was repeated 250 times, resulting in 250 power-difference estimations. The mean and standard deviation of these estimations were computed, with which the measured power-difference was compared using a Z-test with $\alpha = 0.05$.

RESULTS

To present the results, two symmetrical electrodes above the left and right hemisphere were chosen that showed the biggest response to audio-tactile stimulation: electrode F1 (left hemisphere, left pictures) and F2 (right hemisphere, right pictures). Because somatosensory pathways cross between body and brain, tactile information will be processed in the hemisphere contralateral to the stimulated body side, so in the right hemisphere when the left side of the body is stimulated and in the left hemisphere by stimulation of the right body side.

Perception condition

Figure 6 displays the event related spectral perturbations (ERSP) and the inter-trial coherence (ITC) extracted from the induced data responses measured in the perception condition when audio-tactile stimuli were presented. The magenta line indicates the beginning of the stimulation, and the interval between the two black lines is the time period used to calculate power and phase. The left side of the ERSP plot shows how much power is present at each frequency. For example, when the right side of the body is stimulated with 20 Hz, a power increase at 20 Hz can be seen at the left electrode. In addition, a strong inter-trial coherence is present at that same frequency (left side of lower plot).

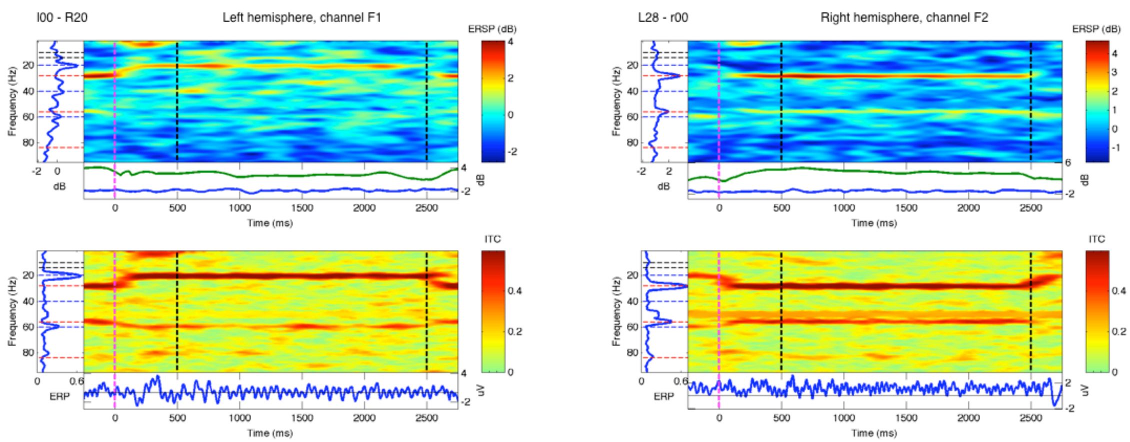

Figure 6. Event related spectral perturbations (ERSPs) and inter-trial coherences (ITCs) in the stimulation conditions l00-R20 (left figure) and L28-r00 (right figure).

The inter-trial coherence seen in figure 6 implies that at least part of the trials are in phase. The distribution of phases, depicted in figure 7, confirms this. The blue line shows the distribution of phases of the 20 Hz analysis, the red line these of the 28 Hz analysis. When the stimulation and the analysis frequency are the same, a strong phase coherence can be seen at that frequency. When a frequency is analyzed that is not presented, phases are uniformly distributed.

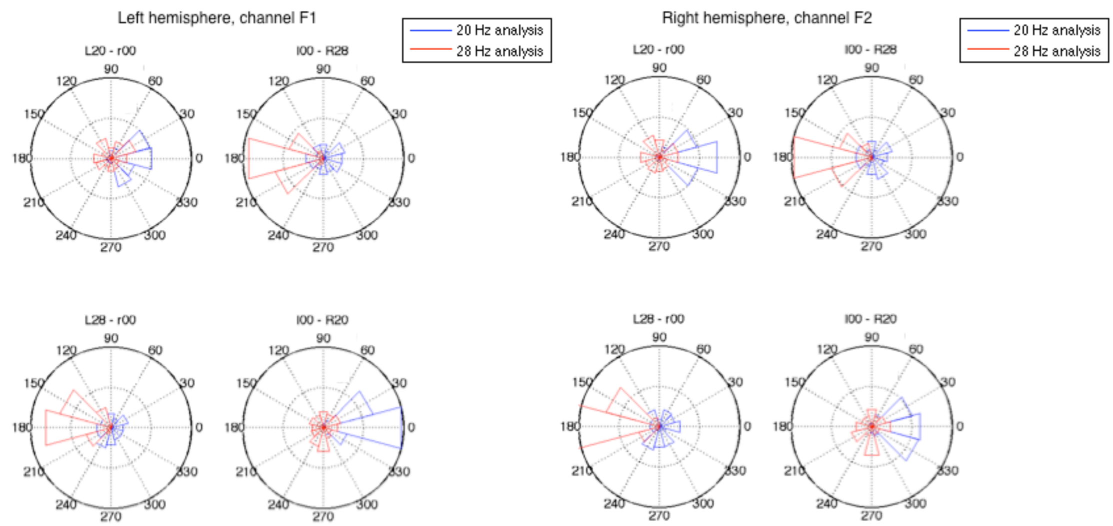

Figure 7. The distribution of phases.

The phase coherence found in the data demonstrates the time-locking of the steady-state responses to the stimulus, and makes it reasonable to analyze evoked activity as well. The grand-averages of the ERPs are shown in the top row of figures 8 and 9. The bottom rows show their corresponding power spectra.

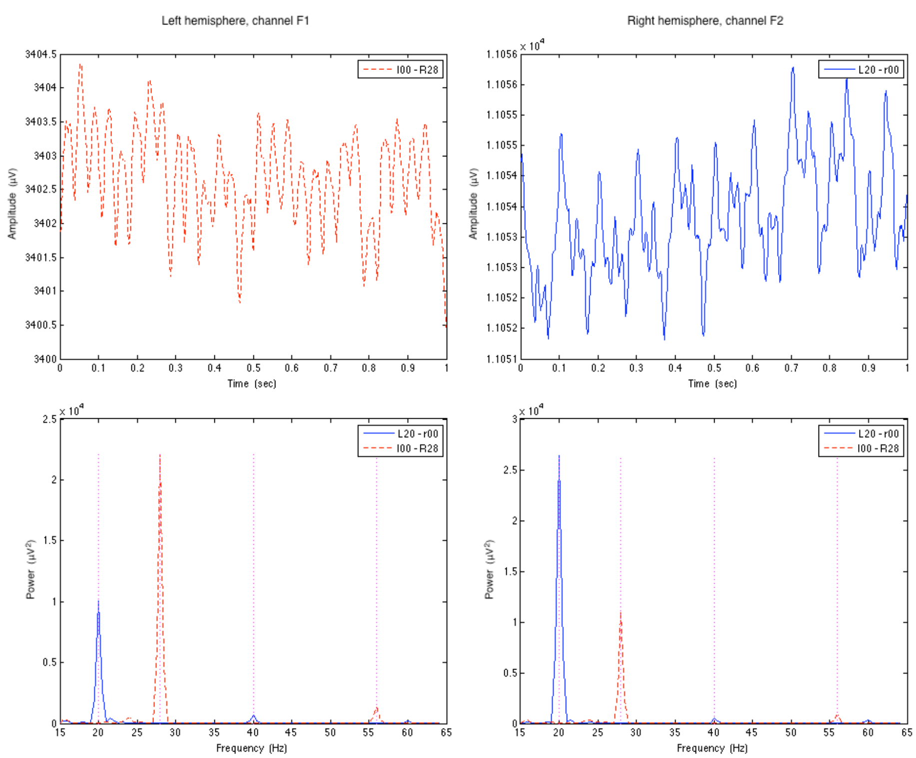

Figure 8. ERPs of the L20-r00 and l00-R28 condition, and their corresponding power spectra.

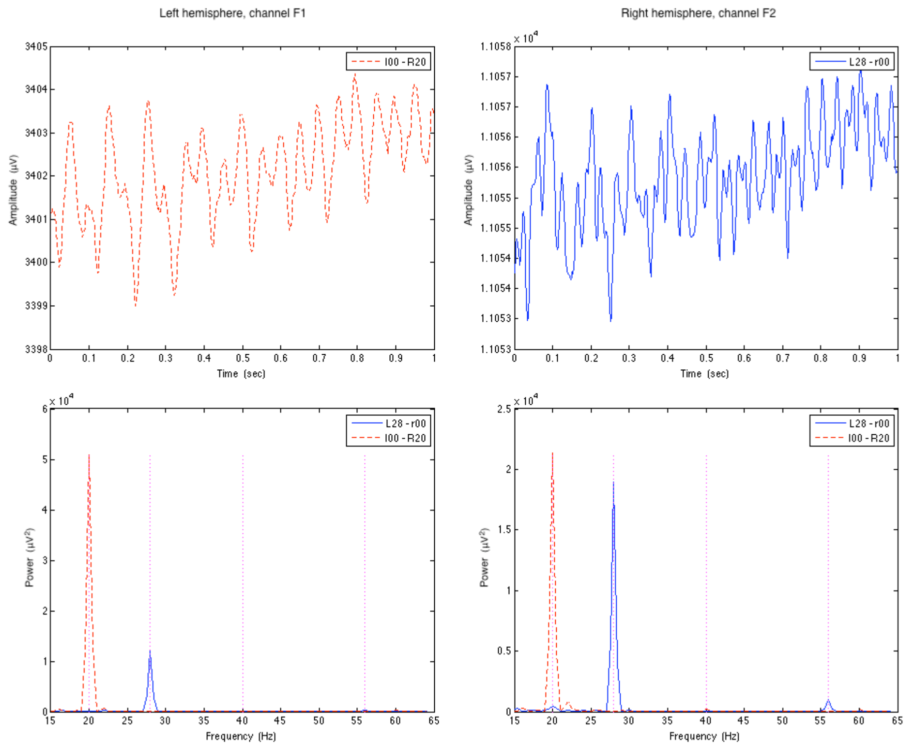

Figure 9. ERPs of the L28-r00 and l00-R20 condition, and their corresponding power spectra.

In the L20-r00 condition (Fig 8, blue line) a clear power increase can be seen at 20 Hz at the contralateral (right) electrode. There is also some power present at the higher harmonics, 40 and 60 Hz, although amplitudes are much smaller (-16.9 dB and -18.5 dB respectively). Even though somatosensory processing is lateralized, due to the electrical conductivity of the skull, ipsilateral electrodes are able to pick up electrical signals generated in the other hemisphere as well. This is why there is also a peak, though much smaller, at 20 Hz present at the ipsilateral (left) electrode (- 4.2 dB). The red line, i.e. the l00-R28 condition, shows a comparable effect: power increases at 28 and 56 Hz at the contralateral left electrode, and smaller peaks at the ipsilateral electrode.

Two conclusions can be drawn from these power spectra: stimulation of the right body side elicit bigger responses than stimuli applied to the left side of the body, and 20 Hz stimulation elicit bigger responses than 28 Hz stimulation. Taken together, biggest responses are evoked by stimulation of the right body side with 20 Hz.

By subtracting the power of two contrasting stimulation conditions, e.g. conditions L28-r00 and l00-R20, power gains by stimulation can be computed. These power gains (third column) and the power per stimulation condition (first two columns) are depicted in scalp maps in figure 10. The rows represent different stimulation modalities (the audio, tactile and audio-tactile modality respectively). Figure 10A displays the amount of 20 Hz power present in the brain when stimulated with different frequencies. In the L28-r00 condition (first column), no 20 Hz oscillations are found. However, this is expected because there is no 20 Hz stimulation. In the l00-R20 condition (second column), there is power present at 20 Hz in left frontal and tempero-parietal areas for the tactile and audio-tactile modalities. However, no power is detected in the auditory modality. The third column depicts the difference between the first two columns, i.e. the power gain by stimulation (l00-R20 minus L28-r00), and the fourth column shows the significance of these power gains (α=0.05). Please note the high scale of the first three columns, thereby making it more difficult to distinguish between the smaller differences. Significant power gains in the 20 Hz analysis are found in contralateral frontal and tempero-parietal for both tactile and audio-tactile modalities, whereas no areas pop out in the auditory modality. Figure 10B displays the 28 Hz oscillations. Again, for both the tactile and the audio-tactile modality significant power gains can be seen at contralateral frontal and tempero-parietal electrodes. For the auditory modality, frontal electrodes display a significant power effect. However, this frontal activity can only be seen in the 28 Hz analysis of the L28-r00 vs. l00-R20 contrast. In the opposite contrast, i.e. L20-r00 vs. l00-R28 (not shown here), no significant areas are found for this modality. For the tactile and audio-tactile modality, the opposite contrast does show power effects comparable to figure 10.

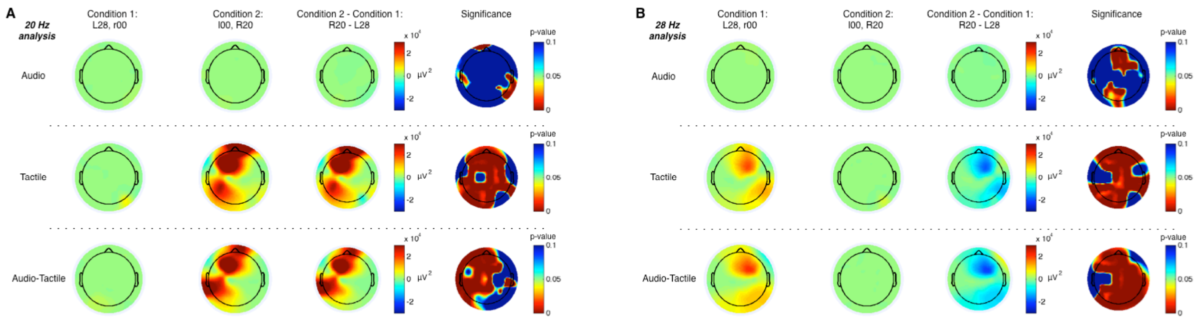

Figure 10. The amount of power present at 20 Hz (A) and 28 Hz (B) on the scalp, in the L28-r00 vs. l00-R20 contrast. The first two columns show the amount of power present in two different stimulation conditions. The third column displays the difference between these two conditions, which represents the power gain by stimulation. The fourth column shows whether these power gains are significant (red areas, α=0.05).

The number of electrodes showing significant power gains (Fig 10, last columns) can then be used to make a comparison between the interesting modalities. For the 20 Hz analysis, more significant power gains are found in the tactile modality compared to both the auditory and audio-tactile modality (58 channels vs. 9 and 45 channels respectively). However, for the 28 Hz analysis, the audio-tactile modality has more significant channels (58 channels) than the auditory (27 channels) and tactile (56 channels) modality. The opposite contrast (L20-r00 vs. l00-R28, not shown here) revealed a comparable result, although for the 28 Hz analysis the tactile modality showed slightly more power effects than the audio-tactile modality (62 vs. 61 channels).

Selective attention condition

The distribution of phases, which is extracted from the induced activity measured in the selective attention condition when audio-tactile stimuli are presented, is depicted in figure 11. Again, strong phase coherences are found at the stimulation frequencies, which rationalize the analysis of evoked activity.

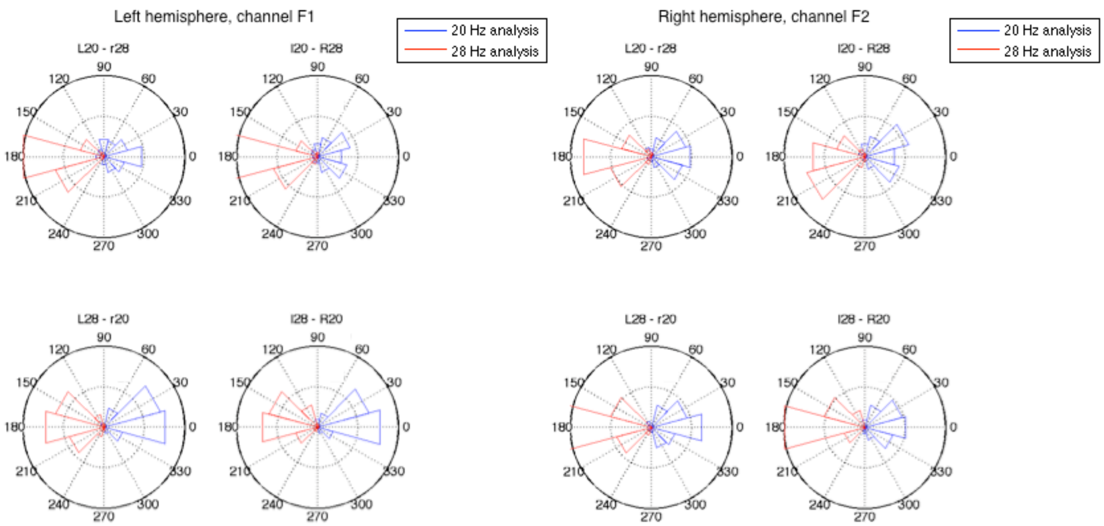

Figure 11. The distribution of phases.

Power spectra extracted from the ERPs are shown in figure 12. The upper row depicts the L20-r28 vs. l20-R28 contrast, the bottom row the L28-r20 vs. l28-R20 contrast. Blue lines illustrate the responses when attention is focused on the left side of the body, red lines the responses when the right body side is attended to. Again, biggest responses are generated by stimulation of the right body side, and when a stimulation frequency of 20 Hz is used. In addition, focusing attention to the right body side seems to amplify the amplitudes of both tagging frequencies, irrespective of which tagging frequency is presented to the right side, suggesting a right hand dominance. However, differences between the two attention conditions (left in blue vs. right in red) are small and seem to be inconsistent.

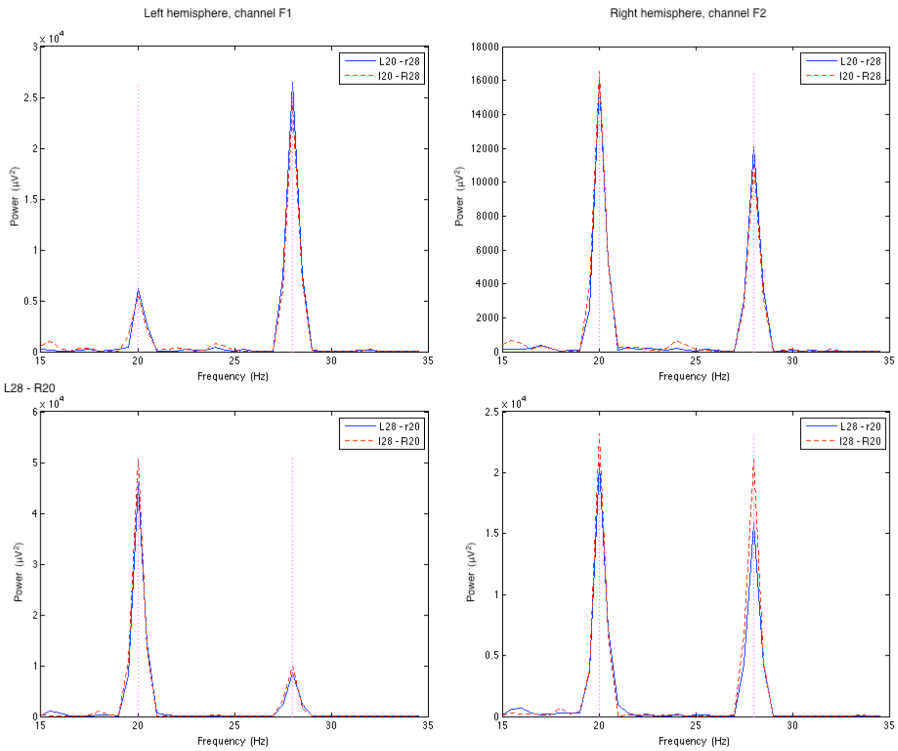

Figure 12. Power spectra extracted from the L20-r28 and l20-R28 condition (top row), and from the L28-r20 and l28-R20 condition (bottom row).

Figure 13 displays the power at each stimulation frequency in scalp maps. Again, the first two columns show the power per stimulation condition, L28-r20 and l28-R20 respectively. The third column displays the difference between these two attention conditions (columns), which represents the power gain by attention, and the fourth column shows for which electrodes these power gains are significant. In general, power gains elicited by stimuli in the tactile and audio-tactile modality seem to be larger when presented at the right side of the body, irrespective of which side of the body is attended to. There are no power gains found in the auditory modality. Although not shown here, power analyses of the L20-r28 vs. l20-R20 contrast show comparable results.

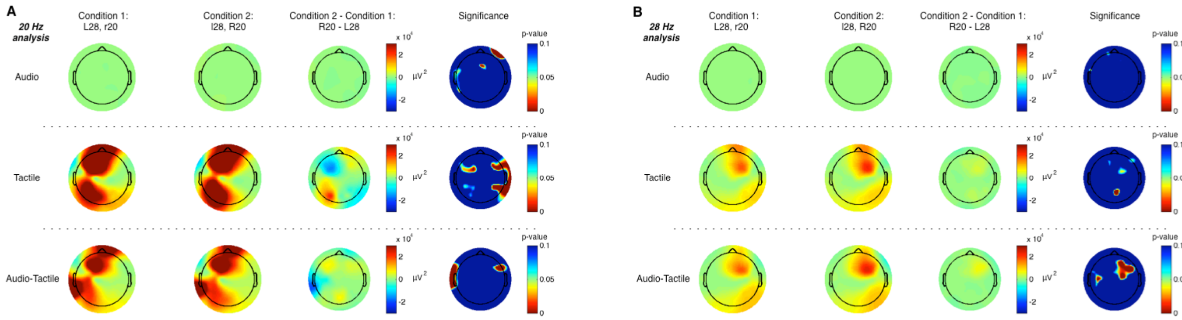

Figure 13. The amount of power present at 20 Hz (A) and 28 Hz (B) on the scalp, in the L28-r00 vs. l00-R20 contrast. The first two columns show the amount of power present in two different attention conditions. The third column displays the difference between these two conditions, which represents the power gain by attention. The fourth column shows whether these power gains are significant (red areas, α=0.05).

Again, the number of electrodes showing significant power gains is used to make a comparison between the different modalities. For the 20 Hz analysis, the tactile modality shows more significant power effects (7 channels) than both the auditory (1 channel) and the audio-tactile modality (3 channels), though the significant locations are unclear. For the 28 Hz analysis, the audio-tactile modality shows more significant power effects (8 channels) than both the auditory modality (1 channel) and the tactile modality (2 channels). However, the direction of the effect is contradictory to what was expected, showing a decrease instead of an increase when the 28 Hz stimulus was attended.

DISCUSSION

In the reported experiment, we investigated the effect of attention on the steady-state response, and the added value of combining stimulation in the auditory and tactile modality compared to unimodal stimulation in either modalities. We hypothesized that stimuli presented at the attended body side would elicit larger steady-state responses in the brain than stimuli presented at the unattended side. In addition, we hypothesized that audio-tactile stimuli would generate responses in the brain that would be easier to detect than the responses generated by auditory or tactile stimuli alone.

A number of different analyses was reported, and will be discussed in turn. First, the analysis of induced activity showed that the responses of trials belonging to the same condition are in phase, thereby demonstrating a time-locking of the steady-state response to the stimulus. This time-locking is found for both the perception and the selective attention condition, thereby rationalizing the analysis of evoked activity for both conditions.

The power spectra extracted from the evoked activity (ERPs) show that the tagging frequencies that were added to the stimuli are clearly present in the brain data, although in different magnitudes for the different modalities. For the audio-tactile stimuli in the perception condition, the lateralization of the responses is as would be expected, with bigger amplitudes in the cerebral hemisphere contralateral to the stimulated body side. However, the selective attention condition does not show this pattern as clearly, i.e. no higher amplitudes in the hemisphere contralateral to the attended body side. In fact, in some conditions the stimuli presented to the unattended body side yield larger responses than the stimuli presented at the attended side, thereby showing a contradictory effect. This effect might be caused by the right-side dominance seen in the power spectra. When the right side is attended to, the amplitude of both tagging frequencies are enlarged, even though one of these frequencies is applied to the unattended (left) side. This power increase for the unattended left side is even larger than the power increase elicited by focusing attention to the left body side, thereby giving the contradictory effect. Although this effect is in contrast with our expectations, if it is consistent, it can still be used for classification. However, further research is needed to support this idea.

The comparisons that were made between the power increases elicited by audio-tactile stimuli and these elicited by auditory or tactile stimulation alone, showed that for the 20 Hz analysis the tactile stimulation yielded more significant power increases at frontal and tempero-parietal electrodes than the auditory stimuli and the audio-tactile stimuli in both the perception and the selective attention condition. Audio-tactile stimuli elicited more power gains than auditory stimuli. For the 28 Hz analysis results are less consistent. In some cases the tactile modality shows the most power increases, whereas in other cases the audio-tactile modality yields more significant power increases.

Though audio-tactile stimulation elicits larger responses in the brain than auditory stimuli alone, tactile stimulation elicits larger responses than audio-tactile stimulation in most cases (especially when the stimuli are presented with 20 Hz), and therefore seems to be the most promising modality for use in BCI-systems.

In the auditory modality, measured steady-state responses are very small, especially compared to the other modalities. A possible explanation of the small steady-state responses measured in the auditory modality, is that the frequency at which the auditory tone is modulated is not the optimal modulation frequency for auditory stimuli. Larger ASSRs have been shown to be evoked by tones modulated with a frequency around 40 Hz (Pastor et al., 2002).

However, when multimodal integration is pursued, as is in this experiment, timing between the different modalities is crucial, and modulation frequencies of the involved modalities have to be equal. Because the optimal modulation frequencies for tactile stimuli are in the 20 Hz range (Tobimatsu et al., 1999), whereas they are in the 40 Hz range for auditory stimuli, a compromise has to be made between the two ranges, detrimental to either one or both SSRs. This finding implies that the auditory and tactile modalities are not good candidates for multimodal integration when analyzing steady-state responses. Perhaps a different combination of modalities, such as visual and tactile stimulation at the same time, would show an increased SSR. This, however, remains to be investigated, and would not be useful in providing an completely independent BCI-system, as the user would still need to have gaze control to selectively look at (and attend to) one visual stimulus out of several.

A possible explanation of why tactile stimuli elicit larger responses than audio-tactile stimuli may lay in the fact that it is easier to focus attention in the auditory domain than in the tactile domain. Because the two auditory streams do not only differ in space (left vs. right ear), but also in pitch (low vs. high tones), they are much more separable, thereby making it easier to focus attention on one of them, and assign detected time interruption to the corresponding stream. In the tactile modality, the stimuli streams only differ in space (left vs. right hand), which makes is much harder to distinguish between them and assign the time interruptions to the right stimulus stream. In addition, because the auditory modality is highly sensitive for temporal patterns, it is quite easy to detect small interruptions in time, and deviant counting in the auditory stream is therefore not that hard. In contrast, time interruptions in the tactile stream are much harder to detect, especially when the stimulation frequency switches every 2.5 seconds. The complexity of the task in the tactile modality automatically demands more attention, thereby eliciting larger responses. When the two modalities are combined, the different streams (left vs. right) are perceived as even more separable than when presented in only one modality. This increased separability and the complementary temporal information coming from the auditory modality makes the task of detecting time interruptions and assigning these interruptions to the corresponding stream easier, thereby needing less effortful attention. This decrease in attention might account for smaller responses in the brain, especially for the decrease in the somatosensory steady-state response, because more information can be obtained from the auditory modality, and the tactile modality is only seen as a supplement, therefore getting less attention. The possible existing multimodal enhancement effect might therefore be overshadowed by this decrease in attention. Interpretation of the current data is especially hard considering that, as of yet, only one subject has been measured. More data is needed to make functional interpretations about the task.

Although these results are somewhat disappointing in the light of the expectations we had, we still see several improvements that may yield good results for BCI. To uncover the patterns of brain activity that we need to classify between the different conditions, other analysis methods may be performed. One of the problems, especially for the auditory modality, is the low signal-to-noise ratio. This ratio might be increased by applying a spatial filter to the data. An example would be running an independent component analysis (ICA), which blindly decomposes the EEG signal to uncover statistically independent components that may represent different sources of brain activity (Makeig, Debener, Onton and Delorme, 2004). Another possibility would be beamforming, which is also a way of spatially filtering the EEG data to virtually ‘zoom in’ on specific brain regions, thereby making use of the a priori knowledge we have of the brain. By applying one of these filters, modality specific signals will be more localized and will be less influenced by other brain signals, thereby giving more information. Future work in this direction will shed more light on the possibilities of further analyses.

Another avenue this research could take, is to try different stimuli. A possibility will be to remove the frequency switches in a stimulation stream. Especially in the tactile condition, these switches are distracting and makes it more difficult to focus attention to one hand. The 28 Hz stimulation is perceived as more salient, thereby automatically drawing your attention to the 28 Hz stimulated hand. More work would be needed to see if the advantages of these switches, in terms of having an extra contrast to analyze, weigh up against the perceptual difficulties this paradigm causes.

As suggested above, to further investigate multimodal integration, two other modalities might be combined, of which their optimal stimulation frequency ranges are closer together, for instance the visual and tactile modality. However, as said before, the use of visual stimuli has other disadvantages when used for ALS patients, e.g. the need of gaze control. The crucial point here is the background knowledge of steady-state responses in different modalities. Although the presented data do not support this idea, multimodal stimuli may have their own specific frequencies that the brain optimally responds to. This however falls far beyond the scope of the current research.

In many BCI-systems that are currently being developed, the optimal frequencies and other features are first detected and fine-tuned for each user individually, and then applied to an online setup. In our case, perhaps the optimal frequencies for SSRs in different modalities may also be different for different people, and allowing the system to adjust for that would greatly increase the detectable response. The downside would be that this would take a lot of calibrating and trying out frequencies, instead of a ready-to-use system that does not require much training and such.

In conclusion, the current data do not support the added value of the integration of auditory and tactile stimuli when making use of the effect of attention on the steady-state response to generate brain signals that may drive a BCI-system, based on the current analyses. However, several other issues still need to be clarified that may still yield results that would change this outlook.

REFERENCES

Birbaumer, N., Ghanayim, T., Hinterberger, T., Iversen, I., Kotchoubey, B., Kübler, A., Perelmouter, J., Taub, E. & Flor, H. (1999). A spelling device for the paralysed. *Nature 398:297-298.*

Calvert, G.A., Brammer, M.J., Bullmore, E.T., Campbell, R., Iversen S.D. & David, A.S. (1999). Response amplification in sensory-specific cortices during crossmodal binding. *NeuroReport, 10:2619-2623.*

Desain, P., Hupse, A.M.G., Kallenberg, M.G.J., de Kruif, B.J. & Schaefer, R.S. (2006). Brain-Computer Interfacing using frequency tagged stimuli. *Proceedings of the 3rd International Brain-Computer Interface Workshop & Training Course 2006*, G.R. Müller-Putz, C. Brunner, R. Leeb, R. Scherer, A. Schlögl, S. Wriessnegger, & G. Pfurtscheller (Eds.), Verlag der TU Graz, Graz.

Farwell, L.A. & Donchin, E. (1988). Talking off the top of your head: toward a mental prothesis utilizing event-related brain potentials. *Electroencephalography and Clinical Neurophysiology, 70:510-523.*

Giabbiconi, C.M., Dancer, C., Zopf, R., Gruber, T. & Müller, M.M. (2004). Selective spatial attention to left or right hand flutter sensation modulates the steady-state somatosensory evoked potential. *Cognitive Brain Research, 20:58-66.*

Hill, N.J., Lal, T.N., Bierig, K., Birbaumer, N., & Scholkopf, B. (2004). Attention modulation of auditory event-related potentials in a brain-computer interface. *Biomedical Circuits and Systems,* 1-3.

John, M.S., Dimitrijevic, A. & Picton, T.W. (2002). Auditory steady-state responses to exponential modulation envelopes. *Ear & Hearing, 23(2):106-117.*

John, M.S., Dimitrijevic, A., van Roon, P. & Picton, T.W. (2001). Multiple auditory steady-state responses to AM and FM stimuli. *Audiology & Neuro-Otology, 6:12-27.*

Kronegg, J., Voloshynovskiy, S. & Pun, T. (2005). Analysis of bit-rate definitions for Brain-Computer Interfaces. *Proceedings of the 2005 Int. Conf. on Human-computer Interaction (HCI'05): 40-46.*

Lins, O.G., Picton, P.E. & Picton, T.W. (1995). Auditory steady-state responses to tones amplitude-modulated at 80-110 Hz. *Journal of the Acoustic Society of Americs, 97(5):3051-3063.*

Macaluso, E. (2006). Multisensory processing in sensory-specific cortical areas. *The neuoscientist, 12(4):327-338.*

Macaluso, E., Frith, C.D. & Driver, J. (2000). Modulation of human visual cortex by crossmodal spatial attention. *Science,* 289(5482):1206-8.

Makeig, S., Debener, S., Onton J. & Delorme, A. (2004). Mining event-related brain dynamics. *Trends in Cognitive Sciences, 8(5): 204-210.*

Müller-Putz, G.R., Scherer, R., Neuper, C. & Pfurtscheller, G. (2006). Steady-state somatosensory evoked potentials: suitable brain signals for brain-computer interfaces? *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 14.

Nangini, C., Ross, B., Tam, F. & Graham, S.J. (2006). Magnetoencephalographic study of vibrotactile evoked transient and steady-state responses in human somatosensory cortex. *NeuroImage 33:252-262.*

Pastor, M.A., Artieda, J., Arbizu, J., Marti-Climent, J.M., Peñuelas, I. & Masdeu, J.G. (2002). Activation of human cerebral and cerebellar cortex by auditory stimulation at 40 Hz. *The Journal of Neuroscience, 22:10501-10506.*

Pfurtscheller, G., & Da Silva, F.H.L. (1999). Event- related eeg/meg synchronization and desynchronization: basic principles. *Clinical Neurophysiology,110:1842-1857*.

Pfurtscheller, G., Neuper, C., Schlogl, A. & Lugger, K. (1998). Seperability of EEG signals recorded during right and left motorimagery using adaptive autoregressive parameters. *IEEE Transactions on Rehabilitation Engineering, 6(3):316-325.*

Rippon, G.A., Scarmeas, N., Gordon, P.H., Murphy, P.L., Albert, S.M., Mitsumoto, H., Marder, K., Rowland, L.P. & Stern, Y. (2006). An observational study of cognitive impairment in amyotrophic lateral sclerosis. *Archives of Neurology, 63(3):345-352.*

Roß, B., Borgmann, C., Draganova, R., Roberts L. & Pantev, C. (2000). A high precision magnetoencephalographic study of human auditory steady-state responses to amplitude-modulated tones. *The Journal of the Acoustical Society of America, 108:679-691.*

Ross, B., Picton, T.W., Herdman, A.T., Hillyard, S.A. & Pantev, C. (2004). The effect of attention on the auditory steady-state response. *Neurology and Clinical Neurophysiology, 22.*

Shimojo, S. & Shams, L. (2001). Sensory modalities are not separate modalities: plasticity and interactions. *Current Opinion in Neurobiology, 11:505-509.*

Stürzebecher, E., Cebulla, M. & Pschirrer, U. (2001). Efficient stimuli for recording of the amplitude-modulation following response (AMFR). *Audiology, 40:63-68.*

Tobimatsu, S., Zhang Y.M. & Kato, M. (1999). Steady-state vibration somatosensory evoked potentials: physiological characteristics and tuning function. *Clinical Neurophysiology, 110:1953-1958.*

Wolpaw, J.R., Birbaumer, N., McFarland, D.J., Pfurtscheller, G. & Vaughan, T.M. (2002). Brain-computer interfaces for communication and control. *Clinical Neurohysiology 113:767-791.*