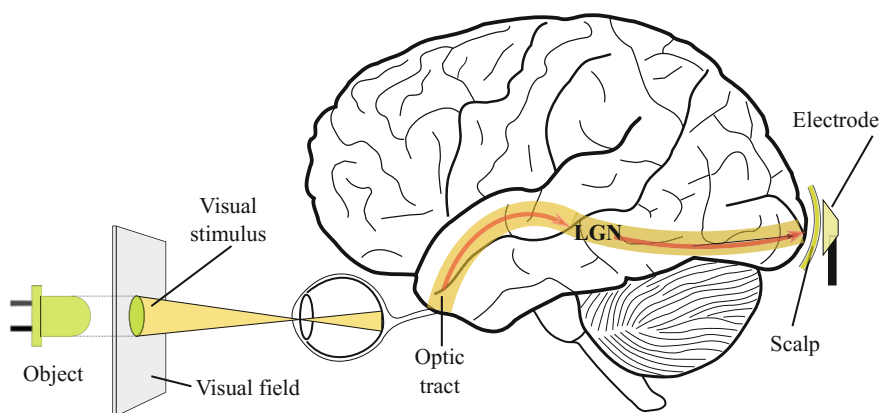


## Chapter 2

# Fundamentals: From Light to Command

In this chapter, a theoretical background is provided. It starts by defining the light and ends by presenting a BCI command due to the light stimulus. Figure 2.1 illustrates the “path of the light” that is emitted by a visual stimulus and sensed by the human visual system [1]. The visual information is carried to the brain visual cortex in which the signal evoked by the object can be measured. A BCI takes the measured signal and translates it into a command. In this sense, basic concepts about light, eye and brain are briefly presented. Next, the image formation, the visual pathway, the topographic representation of the image and the response of visual cortex are described. Then, EEG and VEP are presented. Transient VEP, steady-state VEP and how the refraction errors affect the VEP are discussed. Also, SSVEP-BCI and how the light is translated into commands, are addressed. This theoretical background



**Fig. 2.1** Representation of the visual system, together with a stimulus, visual field and single cell electrode

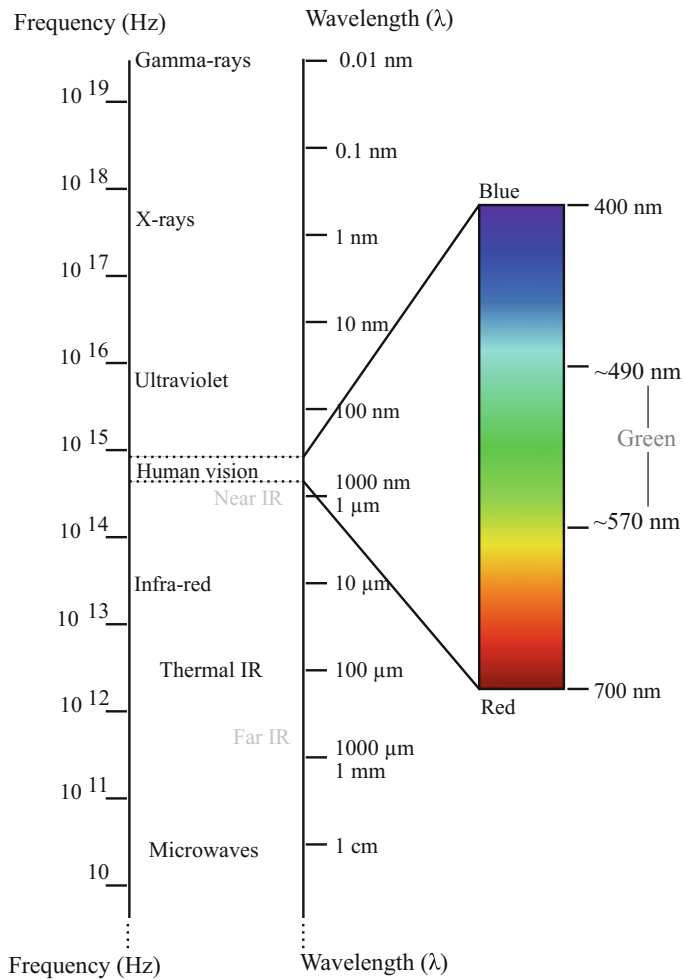
is principally based on well-know medical physiology, optics, neural science and human eye books [1–6]. Finally, a literature review of the more relevant works in the gaze-independent SSVEP-BCI research is performed.

## 2.1 Light, Eye and Vision

Light is a form of electromagnetic radiation emitted by the oscillation of materials electrically charged. Light travels in straight lines unless it encounters an object that causes it to be reflected or refracted when it turns back in the opposite direction or it bends traveling at an angle relative to the original path, respectively. Electromagnetic oscillations have a regular sinusoidal pattern that can be characterized in terms of its wavelength that is perceived as a color. Figure 2.2 shows the electromagnetic spectrum. Visible light includes electromagnetic waves that have wavelengths between 450 and 750 nm, approximately; in which different colors correspond to different wavelengths within this range [3, 7]. All objects reflect light to different degrees and the luminance determine their relative contrasts. Vision is based primarily on the perception of bright-dark contrasts and color contrast enables complex organisms to distinguish surfaces if they reflect different portions of the visual spectrum.

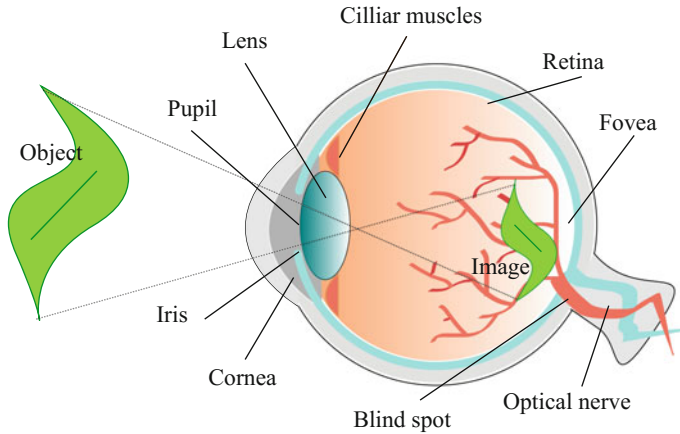
The eye is a complex optic system in the human body that contains about 125 million neurons specialized to turn light into electrical signals called photoreceptors [2]. A schematic diagram of a horizontal, sectional view through a human eye is shown in Fig. 2.3. The cornea and the sclera are the transparent membrane over the front of the eye and the white membrane around the sides and back of the eyeball, respectively. The iris, which is the colored part of the eye, controls the aperture of the pupil regulating the amount of light entering the eye. The pupil is the aperture at the center of the iris, through which light enters the eye. The crystalline lens of the eye or lens is a transparent and flexible structure; by changing its curvature through the contraction or relaxation of the intrinsic muscles of the eye, light coming from different sources is projected on the back of the eye.

Vision is the faculty or state of being able to see. In the human eye, the light enters through the cornea and then passes through the pupil. Gazed objects are projected onto the retinal surface that acts like a movie screen of the eye. Images are projected sharp when lens focuses on the object. Any image formed on the retina should cause nerves to fire sending a signal along the optic nerve to be “seen” by the brain. The retina is the innermost layer of the eye whose function is phototransduction, converting the light energy into the electrical energy. The retinal surface consists of neural tissue that contains the photoreceptors, which are the cells that detect the light waves. Photoreceptors that detect dim light and bright light are named as rods and



**Fig. 2.2** The electromagnetic spectrum. The numbers indicate wavelength in nanometers ( $1 \text{ nm} = 1 \times 10^{-9} \text{ m}$ ). The band between 400 and 700 nm of visible light is highlighted. It was consider green color has primarily wavelength in the 500–570 nm range

cones, respectively. The optic nerve consists of the axons of neurons in the retina; it transmits information from the retina to the brain. The fovea is the central region on the retina, in which light from the center of the visual field strikes. It is the area of the retina with the greatest visual acuity. The optic disk is the portion of the retina where the optic nerve passes through the retina.



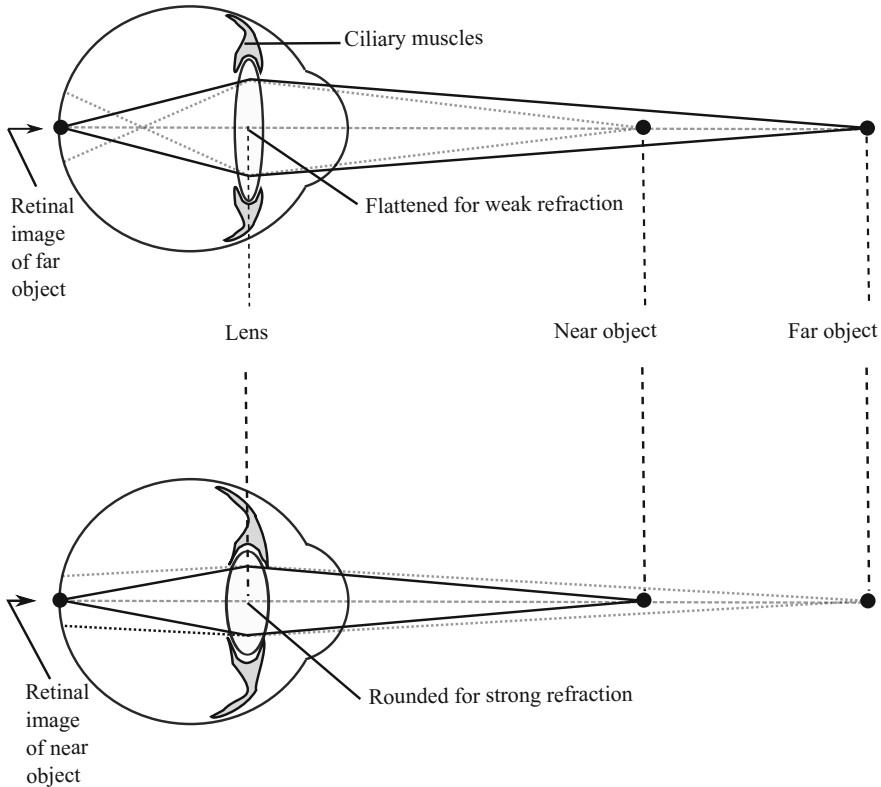
**Fig. 2.3** Schematic diagram of the human eye. The image of the external object passes through the focusing system composed of the lens and the ciliary muscles. The image is projected on the fovea at the center of the retina; note that it becomes inverted in doing so. Due to the optical nerve, the blind spot is the region of the retina without photoreceptors

## 2.2 Image Formation

Light is composed of divergent waves that propagate in all directions from every point of a visible object. Before a sharp image of the object can be projected onto the retina, light must be focused on by the human optical system; then, the light of the projected image reaches light-sensitive receptor cells of the retina; next, signals of receptors arrive at the brain through the visual pathway. Responses measured at the visual cortex are related to the topographic association between retinal and cortex fields [1].

### Focusing the Light

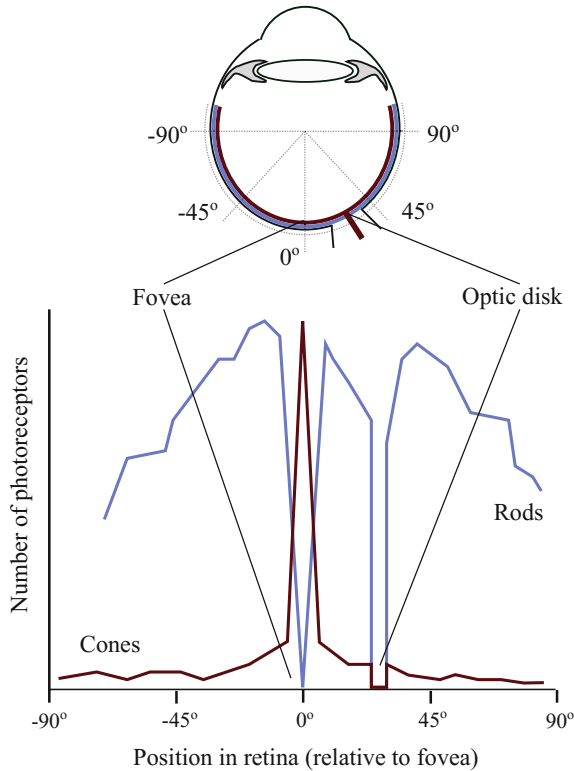
The lens is the primary structure responsible for making adjustments for viewing objects at various distances. The mechanism to adjust the focus of the eye so that we can concentrate the human attention on an object of interest by altering the shape of the lens is called accommodation. Depending on the distance of the object, small muscles attached to the lens, contract or relax, changing its curvature (Fig. 2.4). These muscles are named ciliary muscles. The amount of light entering the eye is controlled by the iris and the pupil. Stimulation of sympathetic nerves to the iris causes these muscles to contract, which then enlarges the pupil, whereas stimulation of the parasympathetic nerves causes the diameter of the iris to get smaller [4].



**Fig. 2.4** Focusing light from distant and near sources. **a** A relatively flat (weak) lens is sufficient to converge the light waves reflected from a distant object on the retina. **b** A rounder (strong) lens is needed to converge the light waves reflected from a near object on the retina

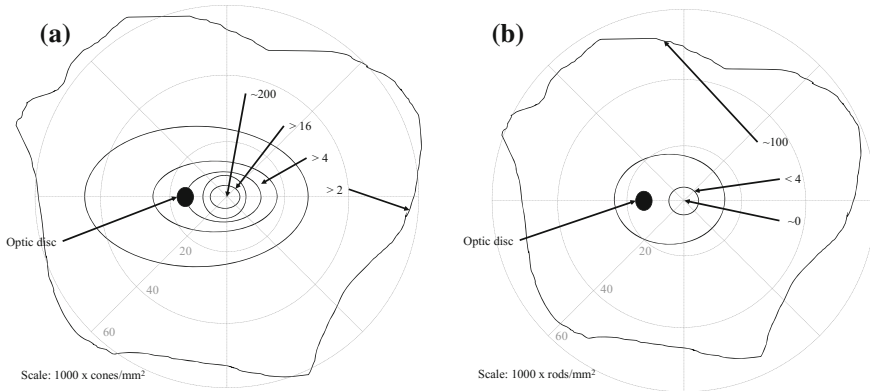
### Imaging the Object

The photoreceptors cones are the cells in which transduction takes place, converting light energy to electrochemical energy that results in patterns of action potentials in the optic nerve. In human eyes, two different types of photoreceptors commonly called rods and cones can be found. Cones are concentrated in the fovea, dispersed retinal pathways and have high acuity in bright light [1]. It makes the fovea essential for daytime vision. This is also the region of the retina where the image of an object of primary interest is being projected. Light-sensitive molecules are activated by specific ranges of wavelengths in the cones. Rods are not present in the fovea and are designed to provide some vision in dim light. Light molecules are activated by a broad range of wavelengths in the rods. Relative distribution of cones and rods are illustrated in Fig. 2.5. The fovea is the region of the retina with a high density of photoreceptors that measures about 1.2 mm in diameter. The fovea is at the center of the inner ring of left and right insets of Fig. 2.5. In this region, cone density increases almost 200-fold, reaching, at its center, the highest receptor packing density found



**Fig. 2.5** Relative distribution of the cones and rods on the retina. The y-axis is the receptor density and the x-axis is the relative distance from the fovea. Note that the highest density of cone receptors is located in the fovea and there are no receptors where the optic nerve leaves the eyeball, thus creating a blind spot. The peripheral vision is primarily due to rods, hence we have minimal abilities to detect colors in those areas

anywhere in the retina [8]. This high density is achieved by decreasing the diameter of the cone outer segments such that foveal cones resemble rods in their appearance. The increased density of cones in the fovea is accompanied by a sharp decline in the density of rods [1, 8], as illustrated by the contour lines of Fig. 2.6. In this book, cones are referred as photoreceptors.



**Fig. 2.6** Contour curves of topographic maps of cones (*Left*) and rods (*Right*) density on the retinal surface. The density of cones on the inner circle of high (exceeds 16000 photoreceptors/mm<sup>2</sup>). The density of rods is very low on the inner circle. The rings are spaced at intervals of about 20°. The fovea is at the center of the inner ring

## 2.3 Field of Vision and Topographic Map

### Field of Vision

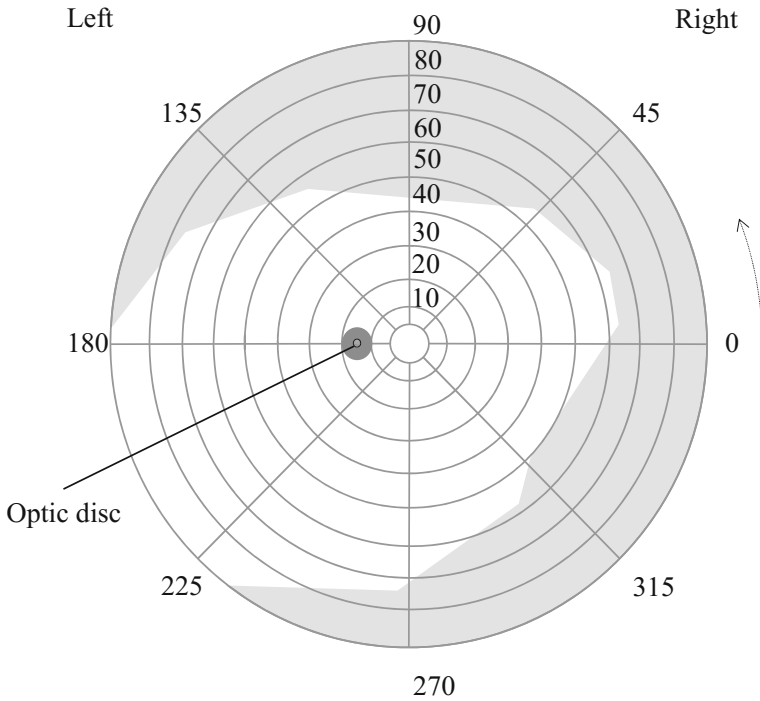
In Fig. 2.7, the field of vision and its perimeter of the left eye is represented [2]. Field of vision corresponds to the visual area seen by the eye at a given instant. It is plotted when the eye is looking toward a central spot directly in front of the eye. Numbers are in degrees, and the eccentricity angle is the distance by which a target is displaced from the fovea. A blind spot caused by lack of rods and cones in the retina over the optic disc is found about 15° lateral to the central point of vision.

### Topographic Map

The representation of different points in the visual field across a population of cortex neurons is called a topographic representation or topographic map. As shown in Fig. 2.8, areas in the primary visual cortex are designated to specific parts of the visual field, as indicated by the corresponding numbers [1]. Beginning with the ganglion cells, each level of the visual system projects to the next level in an organized way so that the map of visual space on the retina is preserved. The area at the center of the visual field (areas 1–4) that corresponds to the fovea is expanded in the cortex so that it occupies about half of the entire cortical representation.

## 2.4 Visual Pathway

The visual pathway is a pathway over which a visual sensation is transmitted from the eyes to the brain [1]. As illustrated in Fig. 2.1, the pathway starts in a receptive field of a cells and can be recorded in a single cell of cortex [9]. The visual pathway includes

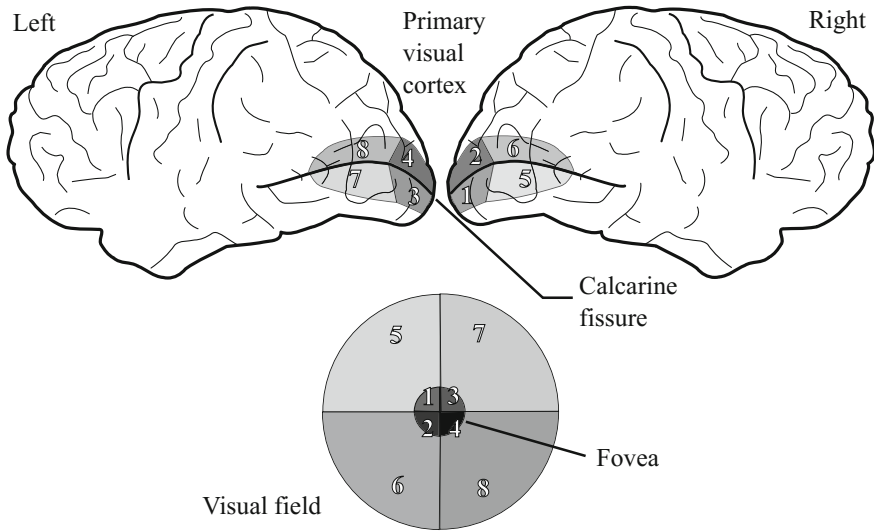


**Fig. 2.7** Perimeter chart showing the field of vision for the left eye. *White* and *gray* regions indicate where the light or object can be seen or it cannot, respectively

the retina, optic nerve, the lateral geniculate nucleus (LGN) and visual cortex, in which (i) the optic nerve is formed by the axons of ganglion cells that are the output neurons from the retina, which generate action potentials that are transmitted to the central nervous system (CNS); (ii) LGN that acts as a sensory relay transmitting information captured by the retina to the visual cortex is composed of six layers; layers 1 and 2 are called the magnocellular layers, while layers 3, 4, 5 and 6 are called parvocellular layers; and (iii) the primary visual area of the cerebral cortex, which is known as striated cortex or cortex V1, is the first stage of cortical processing of visual information. Cortex V1 contains a complete map of the visual field covered by the eyes. It receives its main visual input from the LGN and sends its main output to subsequent cortical visual areas. Cortex V1 is traditionally divided in 6 horizontal layers, with a characteristic distribution of inputs and outputs across layers. Inputs from LGN arrive at layer 4. For instance, this layer is divided into sublayers 4A, 4B, 4C $\alpha$ , and 4C $\beta$ . The main LGN inputs arrive in 4C, magnocellular cells to 4C $\alpha$  and parvocellular cells to 4C $\beta$ .

In summary, the visual system possesses parallel processing, in which segregated pathways transmit different attributes of a stimulus, for example bright and contrast sensations have different pathways. Figure 2.9 show the Parvocellular (or P-pathway)





**Fig. 2.8** Representation of the visual field in the fovea and in the primary visual cortex. This representation is not proportional, for the neural information obtained by the receptors within the fovea projects onto a large portion of the visual cortex

and Magnocellular (or M-pathway) pathways. M-pathway has high contrast sensitivity and does not perceive color. P-pathway is color-sensitive and has low contrast sensitivity. M-pathway (dark gray) starts at the large ganglion cells, projects first into magnocellular layers of LGN and then into layer  $4C\alpha$  primary visual cortex. P-pathway (light gray) starts at small ganglion cells, projects first into parvocellular layers of LGN and then into layer  $4C\beta$  primary visual cortex [1, 2, 9].

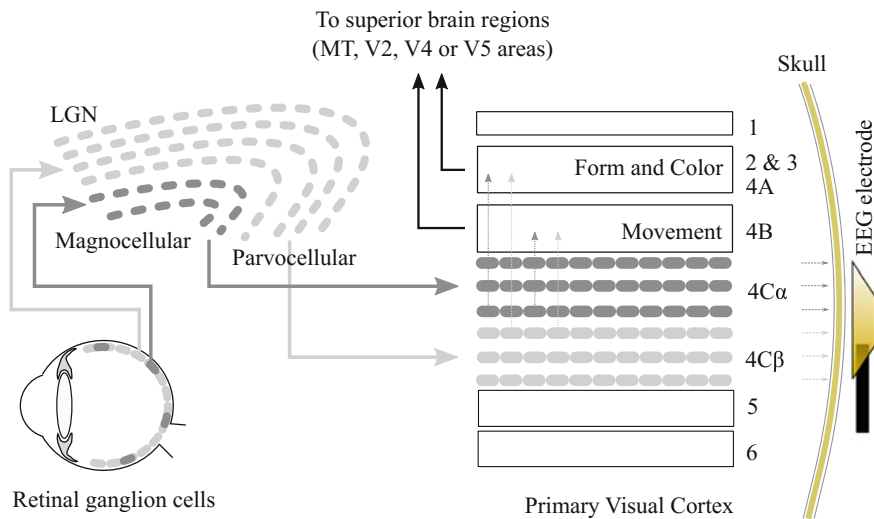
### Response at the Visual Cortex

In general, the visual system processes visual features such as motion, color, form, and depth separately and carries this information in parallel neural pathways [1]. Although information is projected to superior visual, temporal and parietal areas, activity of Cortex V1 can be measured with a non-invasive EEG electrode. Figure 2.10 shows a simplified flowchart of parallel processing for contrast and luminance information, in which the skull effect that is represented by a low-pass filter (LPF) [10] acts over responses of both layers ( $4C\alpha$  and  $4C\beta$ ). EEG signal in visual cortex denoted by  $s(t)$  can be intended as the sum of the response due to parallel pathways with spontaneous EEG denoted as  $\xi$  [11].

## 2.5 Brain Signals and Evoked Potentials

### Electroencephalographic Signals

EEG signals are the neuro-physiologic measurements of the electrical activity of the brain using electrodes placed on the scalp. The resulting traces are known as the EEG waves and they represent the electrical activity of a large number of neurons. The capture of EEG is a non-invasive procedure that reads scalp electrical activity generated by brain structures and frequently used for diagnostic purpose. The electroencephalographic traces, as shown in Fig. 2.11(a), are defined as electrical activity recorded from the scalp surface after being picked up by metal electrodes and conductive medium. Only large populations of active neurons can generate electrical activity recordable on the head surface. Between electrode and neuronal layers, current penetrates through skin, skull and several other layers. Weak electrical signals detected by the scalp electrodes are massively amplified, and then displayed on paper or stored in computer memory. Due to the capability to reflect both the normal and abnormal electrical activity of the brain, EEG has been found to be a very powerful tool in the field of neurology and clinical neurophysiology. Unfortunately, the EEG also reflects activation of the head musculature, eye movements, interference from nearby electric devices, and changing conductivity in the electrodes due to the movements of the subject or physicochemical reactions at the electrode sites. EEG corrupted by other signals are called artifacts [12].

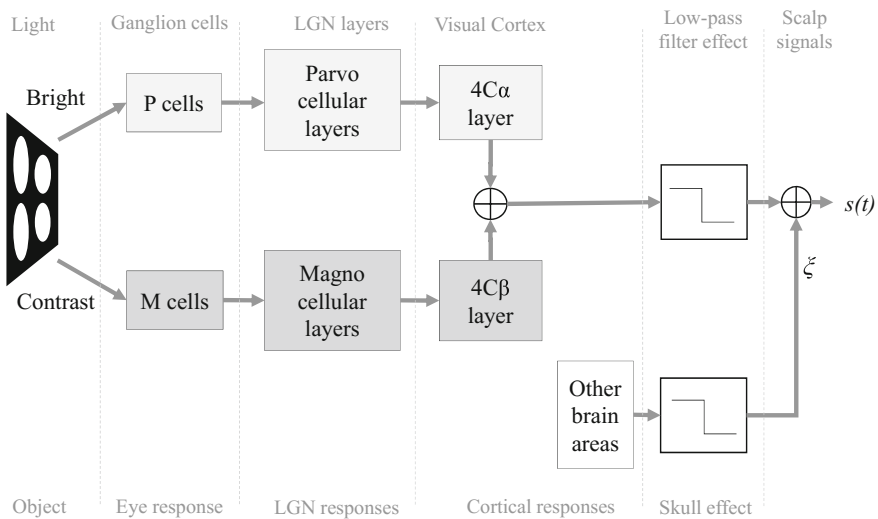


**Fig. 2.9** Functional representation of visual pathways. The magnocellular (*dark green*) pathway starts at the ganglion cells, and arrives at the layer 4Cα of cortex V1 after passing through the layers 1 and 2 of LGN. The parvocellular (*light green*) pathway starts at the ganglion cells, passes through the layers 3–6 of LGN and arrives at the layer 4Cβ of cortex V1. Then, the visual information flows to superior brain regions such as V2, V4 or V5; also called MT

The internationally standardized 10/20 system is usually employed to record the spontaneous EEG, in which the electrode locations are determined by dividing the perimeter into 10% and 20% intervals. An alternative to the 10/20 system is the 10/10 system characterized by intervals of 10% that provides a higher channel density. [13] describe standardization of electrode locations and nomenclature, and evaluate both position systems. Figure 2.11(b) shows electrode positions according to the American Electroencephalographic Society. “The electrodes are named by a capital letter corresponding to the initial of the brain lobe where they are placed (“F”, “C”, “P”, “O” and “T” for Frontal, Central, Parietal, Occipital and Temporal, respectively), followed by an even number for the right hemisphere and an odd number for the left hemisphere. The letter “A” is used for electrodes placed in the ear. For the electrodes placed in the frontal lobe, near the nasion, the letter “p” is added (Fp = Frontal pole). For the electrodes in the line connecting the nasion to the inion, the letter “z” is added”.

### Visual Evoked Potentials

An evoked potential is the electrical response recorded from the human nervous system following presentation of a stimulus that can be detected by EEG and EMG devices. VEP refer to electrical potentials, initiated by brief visual stimuli, which are recorded from the scalp overlying the visual cortex [14]. VEP occurs when a subject observes a visual stimulus, such as a flash of light or a pattern on a monitor. VEP are used primarily to measure the functional integrity of the visual pathways from

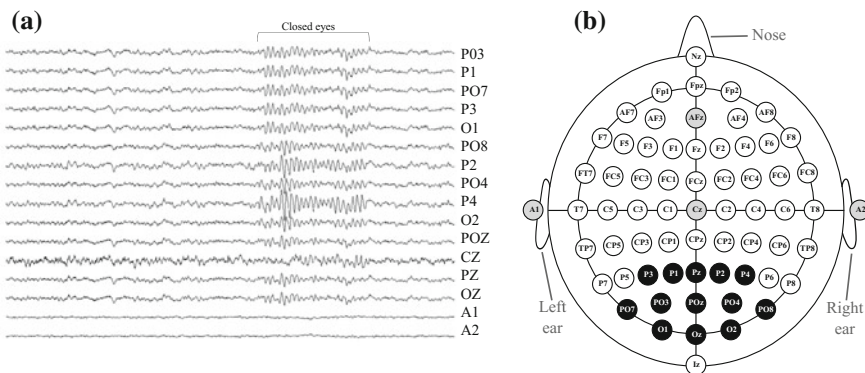


**Fig. 2.10** Simplified flowchart of parallel visual pathways. LGN, lateral geniculate nucleus; M, magnocellular; P, parvocellular. Parvo pathway is composed by P-cell, Parvocellular layers of LGN, and 4C $\alpha$  layer of visual cortex. Magno pathway is composed by M-cell, PMagnocellular layers of LGN, and 4C $\beta$  layer of visual cortex. LPF and  $\xi$  represent the effect of the skull and the spontaneous EEG, respectively

retina via the optic nerves to the visual cortex of the brain [15]. Their waveforms are usually extracted from the EEG signals by averaging. Peak time is measured from stimulus onset to the maximum deflection, positive or negative. Latency is the term employed to indicate the time between stimulus onset and largest amplitude, for positive or negative deflections. The peak amplitude indicates the integrity of the neural structures including axons conducting information along the visual pathway and the latency is related to the time the electrical signal takes to travel from the retina to the visual cortex. The combination of amplitude and latency is helpful in determining the health of the visual pathway [16, 17].

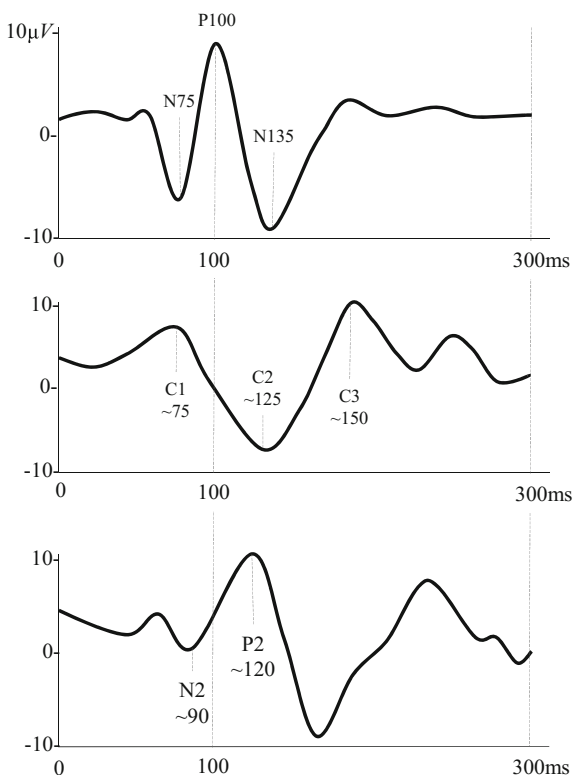
Figure 2.12 shows the VEP waveforms for pattern-reversal, pattern onset/offset and flash stimulation. In the pattern-reversal stimulus, black and white checks change abruptly and repeatedly to white and black checks, respectively. Due to the fact that the stimulus is presented as a kind of checkerboard with equal numbers of black and white checks, there is not significant variation in the luminance. In the pattern onset/offset, the checkerboard changes abruptly with a diffuse gray background. Background has the same luminance of the stimulus. In both patterns, size of checks, stimulation frequency (in reversals per second) and the number of reversals, the mean of luminance, pattern contrast and field size of the stimulus can be adjusted [16]. In flash stimulation, it can be used flashing screens, stroboscopic lights, or light-based portable stimuli. Also, it can be used flickering images in a computer screen, or flickering light mounted on goggles [18]. In that case, the VEP is elicited by a brief flash presented in a fairly illuminated environment.

To plot a well-traced curve, a number of visual responses are obtained by repeating the visual stimulation and then averaging them. Waveforms that allows to measure latency times and amplitude peaks of the responses are called transient responses of the visual system. When stimulation is presented periodically, low repetition rate is required, not faster than two stimuli per second, in order to sensory pathway recovers



**Fig. 2.11** **a** Example of EEG signals of a set of channels with bi-auricular reference and grounded at forehead. Signals of high amplitude and low frequency are signals recorded when the user was asked to close his eyes. **b** Location and nomenclature of the intermediate 10% electrodes, as standardized by the American Electroencephalographic Society

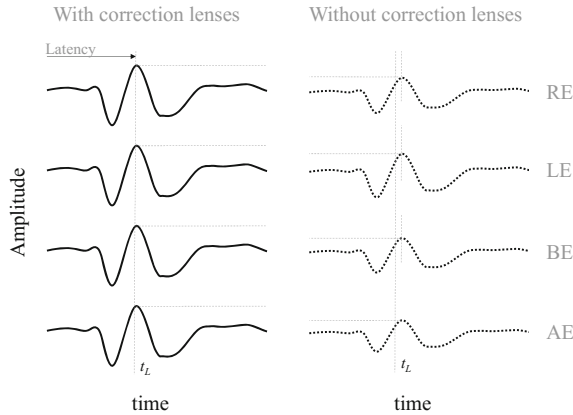
**Fig. 2.12** Typical VEP waveforms for pattern-reversal (*top*), pattern onset/offset (*middle*) and flash stimulation (*bottom*). In pattern-reversal responses, there is two positive peaks at 50 and 100 ms, and a negative peak at 75 ms (P50, P100 and N75, respectively). Responses shows little variation between subjects Onset/offset pattern response consists of peaks at 75, 125 and 150 ms (C1, C5 AND C3, respectively). It show greater inter-subjects variability. In flash responses, peaks can be observed at 30, 90 and 120 ms (N1, N2 and P2, respectively). These responses are more variable than the previous patterns



itself (or resets) before a new next stimulus appears. The top inset of Fig. 2.14 shows the typical VEP response together with the transient response elicited by an pattern-reversal stimulus of 2 Hz. The gray background is used to indicate the period of repetition (500 ms) of the stimulation that is higher than the time of the typical response ( $\approx 300$  ms).

## 2.6 Influence of Refractive Error in VEP

It was found that technical and physiological factors such as pupil diameter or refractive errors affect the VEP [19], because the amplitude of the pattern of an evoked potential is extremely sensitive to optical blurring. In ophthalmology this effect can be used as a means of determining refractive error by measuring the amplitude of the VEP with changes in power of trial lenses [20]. Refractive errors will affect the interpretation of the VEP results, therefore it is important to take the subject's visual acuity into consideration. In the 70s, it was shown that the amplitude of the pattern is sensitive to the optical blurring [17]. Defocusing causes a degradation of the sharp-

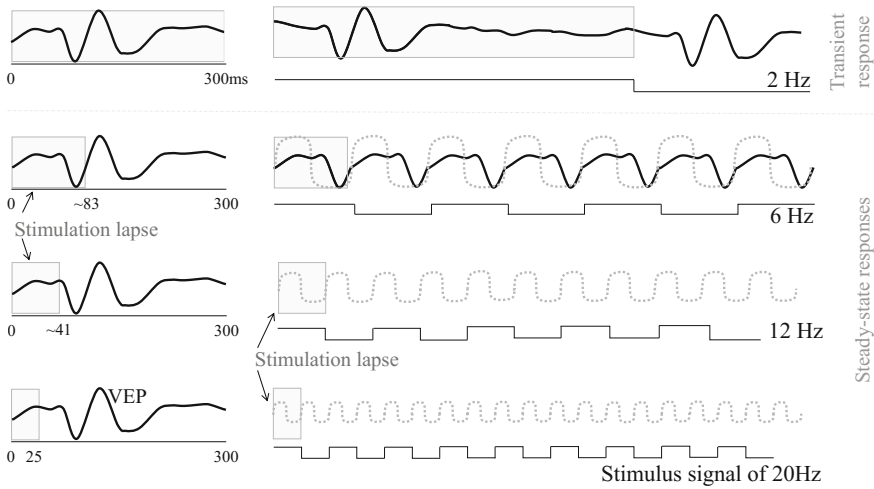


**Fig. 2.13** Comparison between VEP waveforms with (*left curves*) and without correction lenses (*right curves*) of a subject with refraction deficit. From top to bottom, first and second are traces of right (RE) and left eye (LE), respectively; the third trace corresponds to both eyes (BE); and the lowest trace is the grand average (AE) of the potentials.  $t_L$  represents the latency with correction lenses

ness of the contours of the checkerboard. Figure 2.13 shows an example in which VEPs are elicited in one subject with and without lenses [21]. It was using lenses of various dioptric powers to adjust the defocus degree. It can be seen that the VEP amplitude is hardly influenced by refraction errors or by the degree of visual acuity of both eyes or in one of them.

## 2.7 Steady-State VEP

On the other hand, if the stimulation repeated with a fast enough and constant frequency, enough to prevent the evoked neural activity returning to rest (baseline) state, the elicited response becomes a steady-state response. It is called SSVEP and its frequency is directly associated to the stimulation frequency [22]. Figure 2.14 illustrates the steady-state responses for three pattern-reversal stimuli with frequencies 6, 12 and 20 Hz. Note, due to the fact that the neural activity does not return to the baseline state, the waveform of steady-state response (dotted gray curves) are not similar to the typical VEP waveform (black curves) during the stimulation lapse, indicated by gray background. Also, the stimulation lapse causes the amplitude of steady-state responses are different in these three cases. SSVEP waveforms are periodic signals that, like sinusoidal waveforms, can be measured in terms of its amplitude and phase. The amplitude is affected by the stimulation lapse given by the stimulus frequency. As nearly sinusoidal oscillatory waveform, SSVEP contains a fundamental frequency that is related to the stimulus. In steady-state, the brain response is modulated at the second harmonic of the stimulation frequency (twice this frequency) for pattern-reversal stimuli. For flash stimulus, the response is modulated at the fundamental frequency. In general, SSVEP responses vary with the temporal frequency, spatial

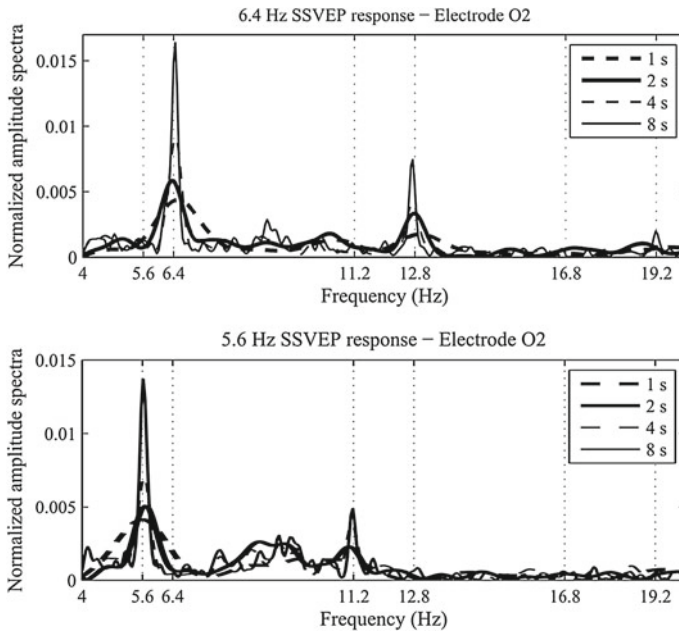


**Fig. 2.14** VEP waveform as a function of stimulation frequency. Note that the wave form is basically modulated at the second harmonic of the stimulus frequency. At the slowest rate (2 Hz) the components of the transient VEP can be seen

frequency (for pattern-reversal and onset/offset pattern), contrast and luminance of the visual stimulus.

SSVEP are better observed in frequency domain because it has characteristic peaks caused by the periodic oscillations in steady-state. These peaks arise in the fundamental and harmonic frequencies of the brain signal. Figure 2.15 shows the SSVEP response in the frequency domain with normalized amplitudes. The top inset corresponds the brain response to a light-emitting diode (LED) stimulus flickering at 6.4 Hz. The curves are the spectrum computed with different signal length or time window (TW). Peaks at fundamental frequency of stimulus are evident in all curves. However, it can be seen that the length of signal influence in the amplitude of peaks. Hence, SNR can be improved by increasing the length of the brain signal [23]. The bottom inset shows the spectral response for the same subject at the same the stimulus but flickering at 5.6 Hz. Peaks in harmonic frequencies can be observed in both cases.

SSVEP can be elicited by several types of stimuli, such as flickering light given by a single LED or an array, flickering image given by single graphics rendered on a computer. The frequency spectrum of the SSVEP due to LED, cathode ray tube (CRT) or liquid crystal display (LCD) are different from each other, as shown in [24]. The frequency spectrum was the simplest for the LED, which only contained the fundamental frequency and harmonics. The spectral responses of CRT contains additionally peaks caused by the monitor refreshing frequency [25, 26]. And the frequency spectrum of the response to LCD presents many low-frequency components in addition to the fundamental frequency and harmonics. Due to the easy way of stimulation by employing computer displays and LED arrays, SSVEP techniques are gaining increasing application in BCI research [27, 28]. They are being used for tagging perceptual and cognitive events, specially in which the employment



**Fig. 2.15** SSVEP spectral response computed by using EEG signals of different lengths (1, 2, 4, 8 s) evoked by visual stimuli flickering at 6.4 Hz (*top inset*) and 5.6 Hz (*bottom inset*)

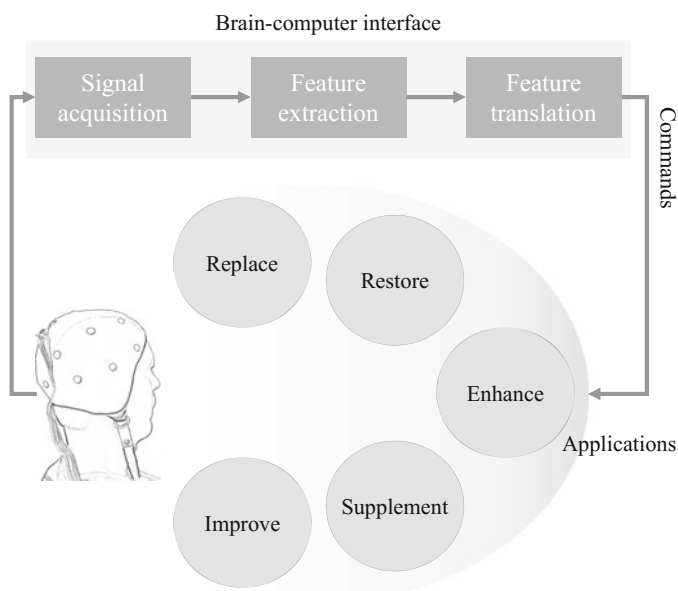
of event related potentials (ERP) are not successful [29]. For example, in the study of attention, two or more objects (such as letters) are presented in different sides of computer screen oscillating at different frequencies. Frequencies that are measured using EEG can show which side is being attended [30].

## 2.8 BCI Based on SSVEP

### Brain-Computer Interfaces

BCIs are systems that could help to restore useful functions to people severely disabled by a wide variety of devastating CNS and neuromuscular disorders, and to enhance functions in healthy individuals [31]. These systems that measure EEG activity and convert it into an artificial output also can replace, enhance, supplement, or improve natural CNS output, as shown in Fig. 2.16; and thereby change the ongoing interactions between users and their external environment [32]. A BCI is a computer-based system that acquires brain signals, analyzes, and translates them into commands that are relayed to an output device to carry out a desired action. Thus, BCIs do not use the brain's normal output pathways of peripheral nerves and muscles. This definition strictly limits the term BCI to systems that measure and use signals produced by the CNS.





**Fig. 2.16** Design and operation of a BCI system. It records brain signals, extracts specific features and translates them into commands. BCIs applications improve, supplement, enhance, restore or replace natural neuromuscular outputs

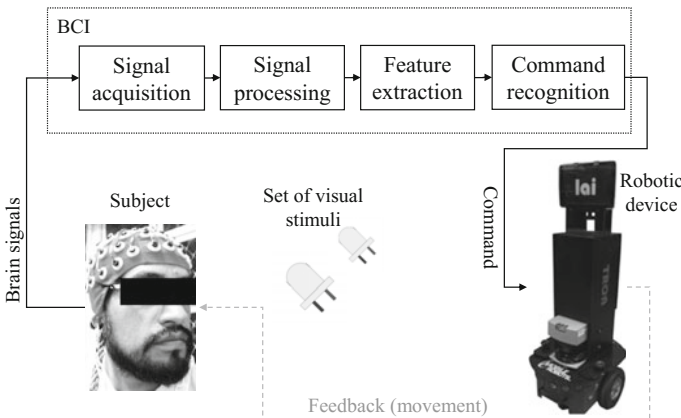
A BCI records brain signals, extracts particular features from them, and translates the features into new artificial outputs that act on the environment or on the body itself. The output could replace natural output that has been lost for injury or disease, and help to restore lost natural output of someone with a spinal cord injury whose limbs are paralyzed. Also, it could enhance natural CNS output of someone who is engaged in a task that needs continuous attention, and supplement natural neuromuscular output of a subject who is able to control, e.g. a robotic arm. In this sense, recent years have seen BCI applications as a novel and promising new channel of communication, control and entertainment not only for people with disabilities but also for healthy people.

### Brain-Computer Interfaces Based on SSVEP

As shown in Figs. 2.14 and 2.15, the waveform of SSVEP is related to the flickering frequency of a visual stimulus and the spectral response presents peaks in the fundamental frequency of the stimulus and its harmonics. In BCIs based on SSVEP, a set of visual stimuli flickering at different frequencies are employed. Each stimulus is associated to a specific command that can be used to control an external device such as robotic wheelchair. Usually, stimuli are presented to users properly, in order to avoid interference between two or more stimuli. To send a command to an external device, users are instructed to attend the stimulus associated with the specific command. SSVEP-BCIs are developed to capture the EEG signals, extract

the fundamental frequency after processing the signal and translate it into an external command [33]. Hence, this kind of BCIs allows users to control external devices by attending a stimulus from a set of flickering stimuli. Currently, the SSVEP-BCI has some advantages over other EEG-based BCI systems, specially when signals are recorded over the visual cortex. It includes (i) a high SNR [18]; (ii) a high Information transfer rate (ITR) [18]; (iii) a less susceptibility to eye movements and blink artifacts as well as to EMG artifacts [34]; and (iv) a very little (or no) training stage, since the VEPs are inherent responses of the brain [18, 35].

Figure 2.17 shows the elements of brain-computer interaction involved in the controlling of an external device given by a telepresence robot. The BCI captures and processes the brain signals before extracting features and recognizing the command associated to the stimulus. Next, a control command is sent to the mobile robot. The SSVEP response depends of the characteristics of the stimulation source. The color, intensity, duty cycle and principally the flickering frequency of the stimulus modulate the response. Software stimulation sources running on a computer consisting of alternate chessboard patterns or dedicated stimulation sources can be used to control intensity and waveform of stimulation signals. SSVEP patterns can be automatically detected through a series of signal processing steps including pre-processing (e.g., band-pass filtering), artifact detection/correction, feature extraction (e.g., spectral content at the stimulation frequencies), and feature classification. BCI performance is usually assessed in terms of classification accuracy, classification speed, number of available choices, and bit rate. In SSVEP-BCI systems, the classification accuracy is primarily influenced by the strength of the evoked response, the SNR, and the differences in the properties of the stimuli. The classification speed depends on the time it takes for the SSVEP to be of sufficient strength. Increasing the number of



**Fig. 2.17** SSVEP-BCI for controlling a robotic device. The BCI captures and processes the brain signals before extracting features and recognizing the command associated to the stimulus. Next, a control command is sent to the mobile robot

targets offers a higher number of possible commands but can decrease classification accuracy and speed [26].

## 2.9 SSVEP-BCI and Gaze Dependence

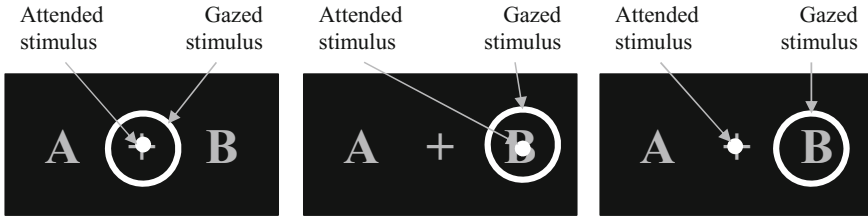
Although the traditional SSVEP-BCI systems are becoming robust systems, they are unsuitable for patients with paralysis who do not have reliable control of eye movements. Due to the fact that these systems demand muscular activity to attend a target stimulus, they are called dependent BCI systems [31, 36]. It means that the features extracted from the EEG signals depends of muscular activity. Consequently, other assistive technologies could be employed to detect the gaze direction. However, in recent years strong evidence suggests that people can shift the attention among stimuli with no gaze movement. This is the basis on the Independent-gaze BCI.

### Selective Attention

Visual-spatial attention refers to the ability to selectively process the relevant events in the visual surroundings and ignore the irrelevant events. Attention can be directed to visual events in two ways; (i) head and eye movements can be employed to gaze directly to an object. This is often referred to as an overt shift of attention, and (ii) alternatively, spatial attention can be directed towards the relevant object or event without movement of the eyes, often referred to as a covert shift of attention. Covert spatial attention allows an observer to attend events independent of eye movements. [37] conclude that covert and overt attention shifts utilize different neural mechanisms. Shift of attention is the mechanism that is employed in SSVEP-BCI to select one of a set of stimuli. It occurs when directing attention to a stimulus increases the efficiency of processing decreasing the processing of irrelevant stimulus. Figure 2.18 illustrates this mechanism, in which white circles and points were placed on the gazed and attended objects, respectively. First figure (left inset) represents an initial stage, in which an object is gazed and attended. The second figure (middle inset) illustrates the overt attention, in which the attention and gaze were shifted together. In the third figure (right inset), only the attention having been shifted, it is called gaze-independent selection because muscular movements are not required to shift attention.

### Current State of Gaze-Independent SSVEP-BCI Research

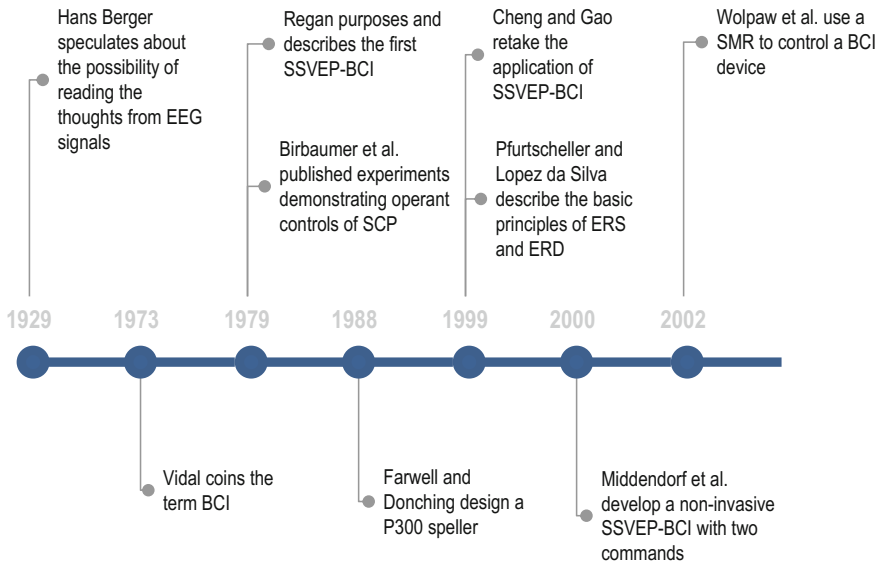
BCI research has been focusing on developing communication and control technologies for people with severe neuro-muscular disorders that could cause partial or complete paralysis. BCIs are using different technologies as EEG, magnetoencephalographic (MEG) [38], electrocorticographic (ECoG) [39, 40], or intracortical recordings to measure the brain activity with high spatial resolution. Also, other signals as functional magnetic resonance imaging (fMRI) are being used to record information with high spatial resolution.



**Fig. 2.18** Covert versus overt attention. *Left* Starting stage where gazing and attention are in the plus symbol. *Middle* Overt attention where both attention and gazing shift from plus symbol to letter B. *Right* Covert attention where only the attention shifts from plus symbol to letter B; Gazing directions does not change

In BCI research area, the most common non-invasive method employed in BCI is based on EEG. In 1929, Hans Berger speculates about the possibility of reading the thoughts from EEG signals [41]. Then, in 70's, the term BCI was coined by [42]. Near 1980, Reagan proposed the first SSVEP-BCI [18] and studies demonstrating control of SCP were published [43]. In 1988, a P300 speller based on ERP was designed [44]. Late last century, applications of SSVEP-BCI were taken into account again [45] and the basic principles of events related to desynchronization (ERD) and events related to synchronization (ERS) were described [46]. [33] develops a non-invasive SSVEP-BCI with two commands. In 2002, sensorimotor rhythms (SMR) were used to control a device with a BCI [31]. Figure 2.19 shows a timeline of the BCI research indicating the year when BCI systems were proposed or developed. In the past decade, experiments to evaluate the number of people that are able to operate BCI based on EEG have been conducted. Regarding to BCI based on motor imagery and ERD, a demographic study conducted by [47] 93% of the subjects were able to achieve a classification accuracy above 60%. Regarding BCI based on P300, in an experiment conducted by [48] achieved 72% of the subjects were able to spell with 100% accuracy. And, regarding to SSVEP-BCI, a demographic experiment conducted by [49] an accuracy average of 95% was achieved.

Although SSVEP-BCI is one of the systems presenting the best results, the disadvantage is given by its muscular dependence because subjects must perform neck, head and/or eyeball control to redirect their gaze direction making it not unsuitable for patients with deteriorated brain motor control. Notwithstanding, SSVEP-BCI systems that do not demand muscular movements are being proposed, for instance, exploring the covert attention as an alternative of stimulus selection. The representative studies in SSVEP-BCI that are not dependent on gaze movements are described briefly below. To see how other BCI systems, such as P300 or motor imagery, are addressing the problem of gaze dependence please refer the study conducted by [50]. Also, [51] perform a meta analysis of BCI in ALS. Figure 2.20 shows a timeline of gaze-independent SSVEP-BCI research, in which systems based on spatial and non-spatial covert attention; and eye-closed systems are presented.

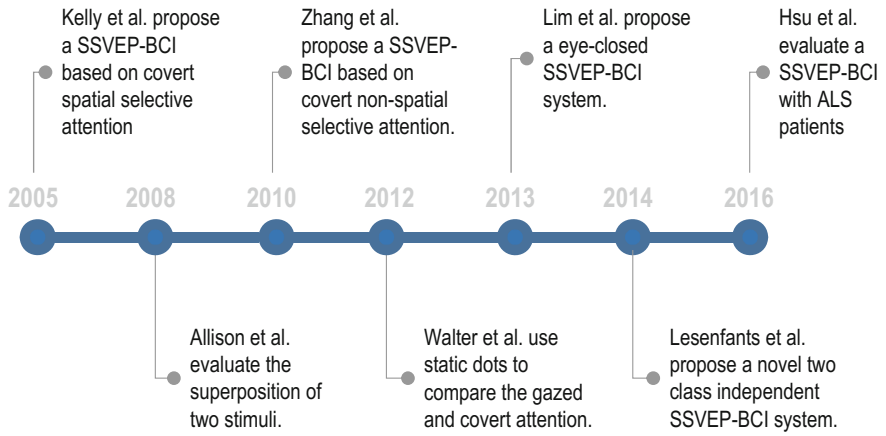


**Fig. 2.19** Time-line of BCI research. It starts at 1929 when Berger speculated about the possibility of reading thoughts, and indicates when BCI systems based on SCP, ERD, P300, SMR and SSVEP was proposed or developed

In a pioneer study, [52] showed that the transition from overt to covert attention in a SSVEP-BCI, allowing a binary decision, resulted in a reduction of classification accuracy by about 20% on average. In light of this performance decrease, the same authors redesigned the paradigm modifying the bilaterally displayed stimuli (visual angle) and obtained an average of binary accuracy of 70.3% [28].

[36] investigated the hypothesis that the superposition of visual stimulation patterns could evoke classifiable changes in SSVEP. They presented the subjects with two images each oscillating at a different frequency. The oscillating images could be presented either in a superimposed or separated condition, in order to explore the role of gaze function on the system performance. In half of the 14 involved healthy subjects, the overlaid condition induced differences in SSVEP activity elicited by the visual stimulation patterns that were robust enough to predict an online BCI control. The authors demonstrated that such SSVEP differences depend on the selective attention paid to one of two superimposed stimulation patterns.

[53] proposed a covert non-spatial visual selective attention paradigm to operate a SSVEP-BCI. Two sets of dots with different colors and flickering frequencies were used to induce the perception of two superimposed transparent surfaces. 18 healthy subjects were asked to selectively attend to one of the two surfaces in order to control the BCI system to perform a binary decision task during a three day training program. An average of accuracy of 72.6% was achieved in the last training session. As reported in Table 2.1 the system would achieve an ITR of 2.17 bits/min.



**Fig. 2.20** Time-line of gaze-independent SSVEP-BCI research. Systems based on spatial and non-spatial covert attention; and eye closed are presented

[54] proposed a novel two-class independent SSVEP-BCI based on covert attention. The influence of feature extraction algorithms and the number of harmonics frequencies were studied. Also, a test with online communication on healthy volunteers and patients with LIS was performed. A newly developed portable light emitting diode-based “interlaced squares” stimulation pattern was employed. Mean offline and online accuracies on healthy subjects (H) were respectively  $85 \pm 2\%$  and  $74 \pm 13\%$ , with eight out of twelve subjects succeeding to communicate efficiently with  $80 \pm 9\%$  accuracy. Two out of six LIS patients (end-users) reached an offline accuracy above the chance level, illustrating a response to a command. One out of four LIS patients had success in online communication.

[55] compared the modulation of SSVEP amplitudes when subjects directly gazed at a flickering array of static dots (overt attention) and when they covertly shifted attention to the dots keeping their eyes at central fixation. A discrimination task

**Table 2.1** Comparison of the accuracy and ITR of gaze-independent SSVEPBCI. **H:** Healthy, **End:** End user, **on:** online, and **off:** offline

Study	Class.	Acc. (%)	ITR (bits/min)	Analysis	Popul.	Subj.	Eye movement
[28]	2	70.3	0.91	Off	H	10	<1°
[36]	2	74	4.18	On	H	14	
[53]	2	72.6	2.17	On	H	18	<1 μV
[55]	2	70.3	0.91	Off	H	14	<25 μV
[56]	2	80	10.8	Off/On	H/End	11/1	
[54]	2	80		Off/On	H/End	12/6	Nothing
[57]	2	83	2.00	Off/On	End	3	

was performed at the attended location to ensure that subjects shifted attention as instructed. Horizontal eye movements (allowed in overt attention but to be avoided in covert attention) were monitored by an electrooculogram. It was demonstrated that overt and covert attention differ in their effect on SSVEP amplitudes and behavior. The lower amplitude modulation by covert attention was considered for both development and application of classification procedures in covert SSVEP-BCIs.

An additional study conducted by [56], which was not identified under the search criteria, performs a classification of binary intentions for individuals with impaired oculomotor function: eyes-closed SSVEP-BCI, allowing users to express their binary intentions without needing to open their eyes. A pair of glasses with two light emitting diodes flickering at different frequencies was used to present visual stimuli to participants with their eyes closed, and recorded EEG patterns were classified in offline/online experiments conducted with eleven healthy participants and one patient with severe ALS. Through offline experiments, it was confirmed that SSVEP could be modulated by visual selective attention to a specific light stimulus penetrating through the eyelids. The online experiment conducted with the ALS patient showed a classification accuracy of 80%.

A recent study evaluated the feasibility of using SSVEP-BCI in young, elder and ALS groups [57]. It was designed for two commands using frontal and occipital positions. Stimuli were based on arrays of 5 LEDs. Seven ALS patients were considered in addition to sixteen healthy people. It was reported that four of them were not capable of completing required tasks. Average of accuracy for healthy people was higher than 90%. While, the accuracy and the ITR for ALS were 83.3% and 2.00 bits/min, respectively for occipital SSVEP. For frontal electrode the values of accuracy and ITR were smaller. Although the focus of this work is not eye movement, it was considered in the present book because end-users were considered in the study.

Table 2.1 summarizes the results achieved by the studies above that include the accuracy and ITR. It can be seen that the three more recent studies performed experiments with end-users. All of them tested their systems with two commands and the highest accuracy rate attained was 80%. The average of the reported ITR was 3.794. In general, results of this Table provide a true overview of the state-of-the-art concerning gaze-independent SSVEP-BCIs. In traditional SSVEP-BCI systems, high accuracy rates are achieved; however subjects must perform muscular movements to redirect their gaze. In SSVEP-BCI systems based on covert attention, subjects do not perform muscular movements; however the accuracy rates are not high. Furthermore, a previous training stage is necessary because subjects must learn to maintain their covert attention on the target stimulus. In this context, a novel assessment is introduced and described in this book, in which subjects select the target stimulus by shifting of focus that does not demand an exhausted training stage because focusing is an optical mechanism that is used naturally by humans throughout life. Also, the focusing mechanism does not demand neck, head or eyeball movements, although these may or may not happen. Patients with paralysis cannot control muscular movements; however, in patients with neurodegenerative diseases such as ALS where the sense of sight is not affected, can retain minimal eye movements, including pupil

and accommodation reflex mechanisms; making focus control possible even in the end stages of these pathologies.

## References

1. Kandel E, Schwartz J, Jessell T (1991) Principles of neural science, 4th edn. Mc Graw Hill, USA
2. Guyton AC, Hall JE (2006) Guyton and hall textbook of medical physiology, 11th edn. Elsevier Inc., Philadelphia
3. Gregory RL (1997) Eye and brain, the psychology of seeing, 5th edn. Princeton University Press, New Jersey
4. Ebenholtz SM (2001) Oculomotor systems and perception. Cambridge University Press, Cambridge
5. Atchinson D, Smith G (2000) Optics of the human eye. Elsevier Science, Edinburgh
6. Howard I (2012) Perceiving in depth: volume 1 basic mechanisms. Oxford University Press, New York
7. Gonzalez RC, Woods RE (2002) Digital image processing. Prentice Hall
8. Packer O, Williams RD (2003) The science of color, 2 edn., chap. Light, the retinal image, and photoreceptors. Elsevier Science Ltd, Amsterdam, pp. 41–102
9. Livingstone M, Hubel D (1988) Segregation of form, color, movement, and depth: anatomy, physiology, and perception. Science, New Series 240(4853):740–749
10. Huggins JE (2010) Brain-computer interfaces. revolutionizing human-computer interaction, chap. BCIs based on signals from between the brain and skull. Springer, Mineapolis, pp 221–239
11. Infantosi A, Lazarev V, De Campos D (2005) Detecting responses to intermittent photic stimulation in the electroencephalogram using the spectral f test. Brazil J Biomed Eng 21(1):25–36
12. Nunez PL, Srinivasan R (2006) Electric fields of the brain. The neurophysics of EEG. Oxford University Press, New York
13. Jurcak V, Tsuzuki D, Dan I (2007) 10/20, 10/10, and 10/5 systems revisited: their validity as relative head-surface-based positioning systems. Neuroimage 34(4):1600–1611
14. Spekreijse H (1980) Evoked potentials, chap. Pattern evoked potentials: principles, methodology and phenomenology. MTP Press Limited, pp 55–74
15. Holder GE (2004) Electrophysiological assessment of optic nerve disease. Eye 18(11):1133–1143
16. Odom J, Bach M, Brigell M, Holder G, McCulloch D, Tormene A (2010) Vaegan: Iscev standard for clinical visual evoked potentials (2009 update). Documenta Ophthalmologica 120(1):111–119
17. Sokol S (1976) Visually evoked potentials: theory, techniques and clinical applications. Surv Ophthalmol 21(1):18–44
18. Vialatte FB, Maurice M, Dauwels J, Cichocki A (2010) Steady-state visually evoked potentials: focus on essential paradigms and future perspectives. Progr Neurobiol 90(4):418–438
19. Kothari R, Bokariya P, Singh S, Narang P, Singh R (2014) Refractive errors and their effects on visual evoked potentials. J Clin Ophthalmol Res 2(1):3–6
20. Sokol S, Moskowitz A (1981) Effect of retinal blur on the peak latency of the pattern evoked potential. Vision Res 21(8):1279–1286
21. di Summa A, Fusina S, Bertolasi L, Vicentini S, Perlini S, Bongiovanni L, Polo A (1999) Mechanism of binocular interaction in refraction errors: study using pattern-reversal visual evoked potentials. Documenta Ophthalmologica 98(2):139–151
22. Russo FD, Teder-salejarvi WA, Hillyard SA (2003) The cognitive electrophysiology of mind and brain, chap. Steady-state VEP and attentional visual processing. Academic Press, pp 259–274



23. Wang Y, Wang R, Gao X, Hong B, Gao S (2006) A practical vep-based brain-computer interface. *IEEE Trans Neural Syst Rehabil Eng* 14(2):234–240
24. Wu Z, Lai Y, Xia Y, Wu D, Yao D (2008) Stimulator selection in ssvep-based bci. *Med Eng Phys* 30(8):1079–1088
25. Herrmann CS (2001) Human eeg responses to 1–100 hz flicker: resonance phenomena in visual cortex and their potential correlation to cognitive phenomena. *Exp Brain Res* 137(3–4):346–353
26. Pastor MA, Artieda J, Arbizu J, Valencia M, Masdeu JC (2003) Human cerebral activation during steady-state visual-evoked responses. *J Neurosci* 23(37):11621–11627
27. Wang Y, Gao X, Hong B, Gao S (2010) Practical designs of brain-computer interfaces based on the modulation of eeg rhythms. In: Graimann B, Pfurtscheller G, Allison B (eds) *Brain-computer interfaces: revolutionizing human-computer interaction*. Springer, Berlin, pp 137–154
28. Kelly S, Lalor E, Finucane C, Gary M, Reilly R (2005) Visual spatial attention control in an independent brain-computer interface. *IEEE Trans Biomed Eng* 52(9):1588–1596
29. Parkkonen L, Andersson J, Hamalainen M, Hari R (2008) Early visual brain areas reflect the percept of an ambiguous scene. *Proc Natl Acad Sci* 105(51):20500–20504
30. Toffanin P, de Jong R, Johnson A, Martens S (2009) Using frequency tagging to quantify attentional deployment in a visual divided attention task. *Int J Psychophysiol* 72(3):289–298
31. Wolpaw JR, Birbaumer N, McFarland DJ, Pfurtscheller G, Vaughan TM (2002) Brain-computer interfaces for communication and control. *Clin Neurophysiol* 113(6):767–791
32. He B, Gao S, Yuan H, Wolpaw JR (2013) Brain computer interfaces. In: He B (ed) *Neural engineering*, 2nd edn. Springer, US, Mineapolis, pp 87–151
33. Middendorf M, Calhoun G, Jones K (2000) Brain-computer interfaces based on the steady-state visual-evoked response. *IEEE Trans Neural Syst Rehabil Eng* 8(2):211–214
34. Lalor EC, Kelly SP, Finucane C, Burke R, Smith R, Reilly RB, McDarby G (2005) Steady-state vep-based brain-computer interface control in an immersive 3d gaming environment. *EURASIP J Appl Signal Process* 19:3156–3164
35. Bin G, Gao X, Wang Y, Hong B, Gao S (2009) Vep-based brain-computer interfaces: time, frequency, and code modulations. *IEEE Comput Intell Mag* 4(4):22–26
36. Allison B, McFarland D, Schalk G, Zheng S, Jackson M, Wolpaw J (2008) Towards an independent brain-computer interface using steady state visual evoked potentials. *Clin Neurophysiol* 119(2):399–408
37. Posner MI, Petersen SE (1990) The attention system of the human brain. *Ann Rev Neurosci* 13(1):25–42
38. Mellinger J, Schalk G, Braun C, Preissl H, Rosenstiel W, Birbaumer N, Kubler A (2007) An meg-based brain-computer interface (bci). *NeuroImage* 36(3):581–593
39. Potes C, Gunduz A, Brunner P, Schalk G (2012) Dynamics of electrocorticographic (ecog) activity in human temporal and frontal cortical areas during music listening. *Neuroimage* 61(4):841–848
40. Schalk G, Leuthardt E (2011) Brain-computer interfaces using electrocorticographic signals. *IEEE Rev Biomed Eng* 4:140–154
41. Birbaumer N (2005) Breaking the silence: Braincomputer interfaces (bci) for communication and motor control. *Psychophy* 43(6):517–532
42. Vidal J (1973) Toward direct brain-computer communication. *Ann Rev Biophys Bioeng* 2:157–180
43. Birbaumer N, Cohen L (2007) Braincomputer interfaces: communication and restoration of movement in paralysis. *J Physiol* 579(3):621–636
44. Farwell L, Donchin E (1988) Talking off the top of your head: toward a mental prosthesis utilizing event-related brain potentials. *Electroencephalogr Clin Neurophysiol* 70(6):510–523
45. Cheng M, Gao X, Gao S, Xu D (2002) Design and implementation of a brain-computer interface with high transfer rates. *IEEE Trans Biomed Eng* 49(10):1181–1186
46. Pfurtscheller G, da Silva FHL (1999) Event-related eeg/meg synchronization and desynchronization: basic principles. *Clin Neurophysiol* 110:1842–1857

47. Guger C, Edlinger G, Harkam W, Niedermayer I, Pfurtscheller G (2003) How many people are able to operate an eeg-based brain-computer interface (bci)? *IEEE Trans Neural Syst Rehabil Eng* 11(2):145–147
48. Guger C, Daban S, Sellers E, Holzner C, Krausz G, Carabalona R, Gramatica F, Edlinger G (2009) How many people are able to control a p300-based brain-computer interface (bci)? *Neurosci Lett* 462(1):94–98
49. Allison B, Luth T, Valbuena D, Teymourian A, Volosyak I, Graser A (2010) Bci demographics: how many (and what kinds of) people can use an ssvep bci? *IEEE Trans Neural Syst Rehabil Eng* 18(2):107–116
50. Riccio A, Mattia D, Simione L, Olivetti M, Cincotti F (2012) Eye-gaze independent eeg-based brain-computer interfaces for communication. *J Neural Eng* 9(4):1–15
51. Marchetti M, Priftis K (2014) Braincomputer interfaces in amyotrophic lateral sclerosis: a metanalysis. *Clin Neurophysiol* 126(6):1255–1263
52. Kelly S, Lalor E, Finucane C, Reilly R (2004) A comparison of covert and overt attention as a control option in a steady-state visual evoked potential-based brain computer interface. In: *Proceedings of engineering in medicine and biology society conference*, vol 2. IEEE, San Francisco CA, USA, pp 4725–4728
53. Zhang D, Maye A, Gao X, Hong B, Engel AK, Gao S (2010) An independent brain-computer interface using covert non-spatial visual selective attention. *J Neural Eng* 7(1):1–11
54. Lesenfants D, Habbal D, Lugo Z, Lebeau M, Horki P, Amico E, Pokorny C, Gomez F, Soddu A, Muller-Putz G, Laureys S, Noirhomme Q (2014) An independent ssvep-based brain-computer interface in locked-in syndrome. *J Neural Eng* 11(3):1–8
55. Walter S, Quigley C, Andersen SK, Mueller MM (2012) Effects of overt and covert attention on the steady-state visual evoked potential. *Neurosci Lett* 519(1):37–41
56. Lim JH, Hwang HJ, Han CH, Jung KY, Im CH (2013) Classification of binary intentions for individuals with impaired oculomotor function: eyes-closed ssvep-based brain-computer interface (bci). *J Neural Eng* 10(2):1–9
57. Hsu HT, Lee IH, Tsai HT, Chang HC, Shyu KK, Hsu CC, Chang HH, Yeh TK, Chang CY, Lee PL (2016) Evaluate the feasibility of using frontal ssvep to implement an ssvep-based bci in young, elderly and als groups. *IEEE Trans Neural Syst Rehabil Eng* 24(5):603–615

Toward Brain-Computer Interaction in Paralysis  
A New Approach Based on Visual Evoked Potentials and  
Depth-of-Field

Cotrina, A.

2017, XVI, 96 p. 61 illus., 13 illus. in color., Softcover

ISBN: 978-3-319-52297-5