5

Neurophysiological Markers for Passive Brain–Computer Interfaces

5.1. Passive BCI and mental states

5.1.1. *Passive BCI: definition*

Recently, brain–computer interface (BCI) development has turned away from its original purpose – namely a subject controlling an effector – and it has focused instead on providing a mental state estimation tool. It is therefore common to speak of "passive" BCIs to refer to systems that no longer employ voluntarily directed brain activity aimed at controlling an effector, but that instead employ signals involuntarily generated by an individual in their task to enrich man–machine communication in an *implicit* manner in addition to monitoring operators in a variety of risky work environments (for example piloting, driving, plant surveillance) [GEO 10, PUT 10, ZAN 11]. This new tool, which brings together neuroimaging and signal processing, satisfies a need in the field of mental state monitoring and makes it possible to respond to a growing need for neuroergonomics. The general structure of a passive BCI is described by Figure 5.1. It covers brain signal acquisition, a processing chain that includes preprocessing and signal conditioning, pertinent marker extraction, translation of those markers and use of that translation to adapt the system or provide feedback. As we will see, different mental states can

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thereby be characterized and estimated by passive BCIs. This estimation is based on a variety of neurophysiological markers that we will discuss in further detail in the following.

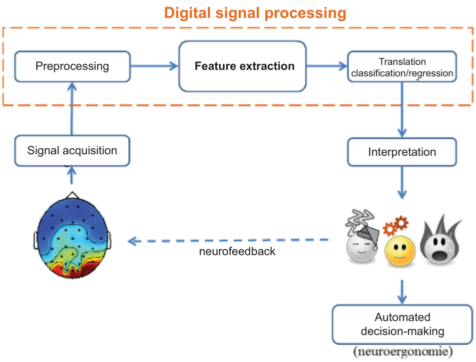

Figure 5.1. *General structure of a passive BC. For a color version of this figure, see www.iste.co.uk/clerc/interfaces1.zip*

5.1.2. *The notion of mental states*

Passive BCIs have the objective of estimating a diversity of mental states, such as the engagement of attentional and cognitive resources – which intersects with attention, mental fatigue and cognitive load – and, as well as it, error detection and the operator's emotional state, to name just a few. Each of these mental states is defined in terms of the cognitive and physiological processes it involves, as well as of behavioral performances and neurophysiological markers. In this chapter, we have focused on electroencephalographic markers of some of the major mental states in the scientific literature. These states are reported separately but it is worth noting that there are interactions between mental states, interactions that operate at the cognitive level and have repercussions at the behavioral and neurophysiological levels. These interactions remain for the most part undocumented and currently existing systems do not take them into account.

5.1.3. *General categories of neurophysiological markers*

BCIs use different kinds of markers extracted from target signals. For example, spectral markers (e.g. power in a given frequency band), temporal markers (e.g. potentials evoked by a given stimulation) and spatial markers (e.g. relative activation of some brain areas) can be used. These three types of markers are described in Chapter 4.

5.2. Cognitive load

5.2.1. *Definition*

Cognitive load can be defined as the task difficulty and the associated effort furnished by the operator to respond to the task's demands. [GEV 07]. It therefore depends on each individual's capabilities and engagement [CAI 07]. The term *cognitive load* is very general, and it is used in research that focuses on variations in task difficulty in terms of:

– the number of items to remember (short term/working memory);

– the number of tasks to be carried out at the same time (divided attention);

– perceptive difficulty (e.g. 3D visual perception);

– temporal pressure (stress).

5.2.2. *Behavioral markers*

The cognitive load's effect on behavior has been extensively explored in the literature. Higher degrees of difficulty will therefore result in a decrease in behavioral performance, whether it is an increase in reaction time or a decrease in response accuracy. For example, using Sternberg's classical paradigm, which requires participants to encode and retrieve items in working memory [STE 66], it has been shown that subjects' reaction time increases linearly with the number of items to memorize [STE 69, GOM 06].

5.2.3. *EEG markers*

From the perspective of frequency, several studies have demonstrated a modulation in the power spectral density of some frequency bands in response to changes in cognitive load levels. Therefore, during increases in cognitive load a decrease in alpha power spectral density (8–14 Hz) at centro-parietal sites (e.g. Pz) is observed along with an increase in theta (4–8 Hz), or even delta (0–4 Hz) power at centrofrontal sites (e.g. Fz) [GEV 00, MIS 06, GOM 06, HOL 09, ANT 10]. Several studies also show variations in the gamma frequency band due to modulations in task difficulty and mental load. [BER 07, OSS 11]. These variations have led to the creation of several indexes, such as the ratio of frontocentral activity in theta and parietal activity in alpha [GEV 03, HOL 09].

With respect to studies focusing on evoked potentials, they have mainly been carried out through concurrent target detection tasks. The amplitude of the P300 component would be a reliable working memory resource allocation index [KOK 01, FU 07]. Indeed, research studies show a decrease in P300 amplitude following an increase in cognitive load [NAT 81, KOK 01, HOL 09, SCH 04]. Beyond the P300 component, some authors have also brought to light a modulation of earlier neuronal components in response to variations in cognitive load. Components N1, N2 and P2 see their amplitude decrease with an increase in load [ALL 08, MIL 11]. Finally, Miller *et al.* have shown a decrease in the amplitude of the Late Positive Potential (LPP) with an increase in the task's difficulty [MIL 11].

5.2.4. *Application example: air traffic control*

There are fields where operators' analytic capacities are continuously requested and where cognitive load can quickly exert significant stress when stimuli become too burdensome. Air traffic controllers follow information coming from several different devices at the same time, and they must quickly react when directions are applied incorrectly or when an unforeseen situation arises. They encounter large volumes of complex information. Although their work environment has been adapted to present data in the clearest manner possible, situations where controllers find themselves in difficulty can still occur. In order to avoid the possibility of dangerous conditions, passive BCIs can help to adapt information interfaces according to air traffic controllers' cognitive load, thereby modulating the difficulty of the task at hand [ABB 14]. Drone controllers face similar difficulties, and in this case too, measuring cognitive load in real time can increase reliability, for example by adjusting the number of drones that an operator can handle at a given time [AFE 14].

5.3. Mental fatigue and vigilance

5.3.1. *Definition*

As reported by Oken *et al.* [OKE 06], *vigilance* is defined differently depending on the field of study and the author. Psychologists and some cognitive scientists thus use the term to designate the capacity to sustain one's attention during the realization of a task for a given period of time, and commonly talk about "vigilance decrement" when subjects' performance decreases with time spent on a task ("time-on-task"; increase in reaction time and detection accuracy). Some authors use terms other than "vigilance", but use the same operational definition. One therefore often encounters the notion of *mental fatigue*, which refers to a state that occurs when a long and tiring task that requires subjects to remain focused is performed, for example when driving a car [LAL 02, KAT 09, ZHA 12, BOR 12]. This mental fatigue affects subjects' capacity to maintain an adequate level of sustained attention and therefore affects their vigilance [BOK 05]. Finally, for neurophysiologists, this term corresponds to a level of physiological alertness on a sleep–wake continuum, without reference to a cognitive or behavioral state. In this book, we will use the term *mental fatigue* to refer to the gradual and cumulative process related to a general reduction in vigilance following an increase in *time-on-task* [LAL 02].

5.3.2. *Behavioral markers*

The state of mental fatigue is traditionally defined as a drop in behavioral performance. Subjects' reaction time thus increases, almost linearly, with an increase in time-on-task [MAC 68, GAL 77, SCH 09, KAT 09, ZHA 12, BOK 05, PAU 97]. Moreover, response accuracy drops as well [PAU 97].

5.3.3. *EEG markers*

In terms of frequencies, a drop in vigilance capacity results in a progressive increase in low-frequency EEG activity [KLI 99, OKE 06, ZHA 12], especially in the lowest alpha frequency band [GAL 77, BOK 05] as well as in the theta band [PAU 97, BOK 05, ZHA 12]. This increase is accompanied by a decrease in high-frequency activity [KLI 99, LAL 02, OKE 06, ZHA 12, FAB 12].

With respect to evoked EEG activity, the amplitude of the P3 component decreases with a drop in vigilance [KOE 92, MUR 05, OKE 06, SCH 09]. Other authors argue that its latency also increases [KAT 09, ZHA 12]. Finally, with respect to the earliest components, the amplitude of the N1 component decreases with time-on-task at the parietal electrodes [BOK 05, FAB 12], whereas the amplitude of the N2b component increases at the central electrodes [BOK 05].

5.3.4. *Application example: driving*

Driving a car is one security and public health hazard for which passive BCIs could help to reduce the number of accidents. If a large number of simpler devices, such as eye movement recording, make it possible to detect microsleep states, EEG can help to prevent dangerous behavioral mistakes even earlier [BLA 10]. Still at the prototype stage, passive BCIs are studied using driving simulators [LAL 02]. Their performance makes it possible to hope that one day they could be used to increase road safety.

5.4. Attention

5.4.1. *Definition*

Selective temporal and spatial attention is the capacity to detect and select a specific target item that is relevant for a given task (for the purpose of deep processing) and to ignore distractors when these items are presented simultaneously or sequentially [HIL 73, POS 80]. This capacity for selective attention to important events that require a specific action can be essential in an ecological context (i.e. in day to day tasks). It is, for example, required in surveillance tasks for operators in a nuclear plant, for air traffic controllers [FU 07] or for car driving and airplane or spaceship piloting, which are more or less demanding and prolonged.

5.4.2. *Behavioral markers*

In the same way that behavioral performance is degraded with an increase in cognitive load or mental fatigue, a decrease in the attention devoted to a task or a stimulus produces a decrease in the individual's performance [POS 80, MAN 95]. Posner *et al.* thus show that we are much quicker in detection tasks when we previously pay attention to the place where the target will appear [POS 80].

5.4.3. *EEG markers*

A task typically used to study selective attention is the oddball task. This task consists of detecting a target item, which is generally rare (present in 10–20% of cases), from among a sequence of frequent distractor items (80–90% of cases) [FIT 81, FRI 01, KOK 01]. Depending on the study, subjects must count the rare target items or perform a specific response to them (e.g. press a button only for the targets, or press different buttons according to the items). In this kind of task, selective attention is accompanied by the item's occurrence probability effect. The typically observed result for this task, when performed in the visual modality, is a modulation of the P300 component evoked at parietocentral and occipital sites by processing items according to their frequency of appearance. Indeed the P300 of a target item will be more ample and longer than that of distractor item, with the amplitude difference being greater when the target item is more rare [HIL 73, PIC 92, KOL 97, FRI 01, GOM 06, FU 07]. This is why that component is also frequently studied in the context of active BCIs, more specifically for the P300 speller paradigm [GRA 10].

Other earlier neuronal components are also modified by this selective attention to a kind of items, with for example greater amplitude of the N1 component for target items than for distractor items at the vertex in the auditory modality [HIL 73], and at the parietal electrodes in the visual modality [FAB 12]. Finally, the N2b component has a larger amplitude for targets than for distractors at the central electrodes [BOK 05].

With respect to frequency EEG markers, frequent and rare item processing differs in terms of the activity evoked in the delta, theta and alpha bands at the frontocentral and parietocentral sites, with a prolongation of this activity in the case of rare items [KOL 97, BAS 92, YOR 98, ONI 09].

5.4.4. *Application example: teaching*

If there is one environment where attention tends to drastically drop despite the best intentions, it is teaching. What teacher has not feared the terrible 2:00 PM slump, right after lunch, when only empty stares respond to even the most eloquent presentations? And there is a population of students that suffers more than the others from this difficulty in selecting and processing information for prolonged periods of time; it is children suffering from attention deficit disorder. Bring the two together, add a spoonful of virtual reality, sprinkle in some passive BCIs, and you get a system that allows students to overcome their difficulties by controlling the presence of distractors in their simulated environment and rewards those that manage to remain attentive [CHO 02].

5.5. Error detection

5.5.1. *Definition*

It is the individual that is ultimately measured by the yardstick of passive BCIs. So we take the notion of an "error" in a subjective sense here. For a user, an error occurs when the result of an action is different from what he or she expected. It is not a question of whether it is "true" or "false", like evaluating responses to a questionnaire or performing a task. It is the representations that a person has of his or her environment that count. We can distinguish between the following four different types of errors [FER 08]:

– a response error is detected in operators that realize they have committed a mistake;

– an interaction error occurs when a system reacts in an unexpected manner;

– an observation error is generated by monitoring a third person;

– a *feedback* error is detected when a sanction (reward or punishment) is different from what was expected.

5.5.2. *Behavioral markers*

Although the *production* of errors is not the focus of this text, a person's capacity to detect an incongruent event directly depends on his or her vigilance state and on his or her attention level. Once an error has been detected, either the operator seeks to rectify it if he or she can influence the system, or, as is often the case in the context of learning, he or she modifies his or her internal representations to adapt to it.

5.5.3. *EEG markers*

Error detection employs evoked potentials, referred to as “error potentials” in that context, with their main recording site at FCz [SCH 00, PAR 03]. Both negative and positive potential components are studied. They make it possible not only to determine if a mistake has been detected but also to identify the kind of mistake at hand. It is even sometimes possible to measure error potentials without the person becoming aware of their mistake [NIE 01].

In the execution of a simple task like target selection, a negative component occurring after 80 ms is characteristic of a response error [FAL 00], a 250 ms delay is associated with a feedback error [HOL 02] and the late presence of a positive component denotes an interaction error [FER 08].

5.5.4. *Application example: tactile and robotic interfaces*

What can be more annoying than a computer that does not do what we ask of it? We press a button and the wrong menu appears; we press a key and it erases in a single blow the last 6 months’ work – which we had never taken the time to save. There is much to be impatient about. And the cherry on top: the more interfaces evolve, the more we have the impression that computers take a sick pleasure in only doing things their way. But no need to panic; the outlook is not quite that somber. Using EEG to detect interaction errors is a step forward in creating systems that self-correct when they provide an inadequate response, for example with tactile [VI 12] or gesture [CHA 10] interfaces. This may be much more useful when what is on the other end of the wire is not a static computer but rather a robot happily bouncing around its hundreds of pounds of alloy, which is a bit more concerning. In this case too, error recognition could make it possible to correct an inadequate behavior in a matter of seconds, whether it is in interaction with a human [FER 08] or when a human is merely observing the machine [ITU 10].

5.6. Emotions

5.6.1. *Definition*

As shown by Paul Ekman through his studies of different cultures, there is a universal component in the recognition of emotions and by extension in emotion production [EKM 99]. There are different nomenclatures for classifying and describing emotions. The most commonly used distinguishes between two dimensions: *valence* and *arousal*. Valence corresponds to the "quality" of an emotion and varies from negative (e.g. "pain") to positive (e.g. "joy"). The second axis, arousal, accounts for the emotion's "intensity level". We can say that "boredom" has a low level of arousal, whereas "terror" possesses a high level of arousal [PIC 95].

5.6.2. *Behavioral markers*

We have abandoned some philosophical notions that, by opposing mind and body, tended to dissociate reason from emotions. Recent work in neuroscience has shown that the emotional component is inextricably related to decision-making mechanisms [DAM 94]. Emotions make it possible to decide more quickly between competing alternatives, with a positive valence being able to guide a choice. They also have an effect on behavior that can be described by the notions of approach and avoidance. When we compare our reaction time between negative and positive stimulation, we are quicker to avoid dangerous situations and faster to approach objects that seem to provide a reward [CHE 99].

A high arousal state brings about several physiological changes, but the inverse is also true, and an increase in metabolic activity, like heartbeat acceleration, can instill emotions and influence our reactions [SCH 62]. Studying emotions also makes it possible to uncover the differences that mark some populations. Children thus have difficulties distinguishing variations in emotional intensity [POS 05].

5.6.3. *EEG markers*

More often than with other mental states, emotional state detection using data exclusively drawn from neuroimaging lends itself to controversy. Indeed, with passive BCIs, EEG is often used, a tool that *also* records the facial muscle contractions that we have trouble avoiding making when we are experiencing heightened emotions. This accounts for the special care that must be taken when performing measurements [HEI 09].

This being said, several markers have been associated with emotional state measurements. Power spectral density in the alpha band in the frontal lobes can correlate with emotional valence. Negative valence is correlated with decreasing power in the left lobe, with a positive valence instead being related to an asymmetry within the right lobe [MOL 09]. The arousal level associated with a stimulus is itself more easily detectable in the theta band, or by studying the amplitude of the evoked potentials [MOL 09].

Beyond the signal's nature, studying the structures activated during an emotional response makes it possible to identify the trigger, either images or sounds [MUH 11].

5.6.4. *Application example: communication and personal development*

No one will be surprised to read that emotions make it possible to directly communicate one's feelings. That seemingly banal statement, nevertheless, indicates the potential for BCIs that can be used to reveal the affection we feel toward lifeless objects – such as robots – be it inclination or aversion [STR 14]. Fortunately, new technologies also help to increase the social link between flesh and bone humans. Even though in this case the measurement relies more heavily on muscle activity than on brain waves, Necomimi ears developed by the *neurowear* team are a shocking example of the kind of enhancement we could benefit from. They are large plush cat ears that are supposed to move in such a way that reflects the user's emotional state. Interacting with peers becomes a much more honest affair. For those who already have trouble tolerating those around them, they may rest assured that EEG measures can also help them take charge, like in social stress situations [JEU 14]. This kind of research is part of the trend to employ *neurofeedback*, as will be discussed in Chapter 13.

5.7. Conclusions

Thanks to technological developments brought about by active BCIs, passive BCIs have been able to see the light of day and are fully expanding. Their contributions are numerous, going from basic research in cognitive neuroscience (with a better understanding of the neurophysiological phenomena that underlie cognitive functions) to human factors (with the development of embedded systems that make it possible to enhance safety in high-risk work environments or piloting situations), as well as the improvement of BCIs. Although several markers of different mental states have already been identified, they often intersect, which can thus disturb recognition systems in ecological settings. Moreover, interactions between mental states can alter markers' relevance. Research should therefore focus on identifying markers that are robust to the type of task performed by operators and to interactions between mental states.

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