Instituto de Bioingeniería
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Analysis of neural substrates and physiological responses involved in the processing of primary emotions

Memoria de Tesis Doctoral

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To whom it may concern:

The doctoral thesis developed by me, Jennifer Sorinas Nerín, and supported by the FPU13/01842 grant of the Ministry of Education of Spain, with title: "**Analysis of neural substrates and physiological responses involved in the processing of primary emotions**", is a compendium of publications and includes the following publications in which I am the first author:

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I declare that these publications have not been and will not be used in any other thesis.

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Informa FAVORABLEMENTE el depósito de la Tesis presentada por Dña. Jennifer Sorinas Nerín,

Realizada bajo la dirección del Dr. Eduardo Fernández Jover,

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El Dr. Eduardo Fernández Jover, Catedrático de la Universidad Miguel Hernández de Elche,

Autoriza la presentación de la Tesis Doctoral titulada "**Analysis of neural substrates and physiological responses involved in the processing of primary emotions**", realizada por Dña. Jennifer Sorinas Nerín (DNI 73204783S) bajo su inmediata dirección y supervisión en el Instituto de Bioingeniería de Elche, perteneciente a la UMH, y que presenta para la obtención del grado de Doctor por la Universidad Miguel Hernández.

Y para que así conste, y a los efectos oportunos, expiden y firman el presente certificado en

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Abstract / Resumen

Abstract

Emotions are a key process in the evolution of species and in particular in the development of human beings. They influence most of the neuronal processes that take place in our day to day, from decision-making, communication and social relations, selective attention, learning and memory. Understand their physiology and neurobiology is a great challenge, still unanswered, which has been raised since Greco-Roman times. The large number of applications from the clinical, for the diagnosis and treatment of mood disorders, to the improvement of brain-computer interactions applicable in both patients and healthy individuals, is unimaginable; so that getting a system capable of recognizing emotions in real time is the holy grail of affective neuroscience today. However, the lack of a theoretical model that defines the term itself, as well as its primary components and mechanisms of action, causes a great variability between the results and computational models that try to solve the equation. In order to be able to establish a real-time emotion classification model, it is necessary to establish a series of previous parameters, such as the emotional model to follow, the optimal window time to extract the features that encode emotional information, the feature extraction method, how many and which are the features that represent the processing of emotional information and the appropriate algorithm to classify this type of information and signal. Based on the dimensional model of emotions, specifically the dimension of valence that characterizes the positive or negative degree of a stimulus generating responses of approach or withdrawal, respectively; we have tried to specify the parameters necessary to develop a computational model that allows us to recognize emotions on the scale of emotional valence focused on real-time applications. For this purpose, we have analyzed the electroencephalographic, electrocardiographic and skin temperature signals of 24 volunteers during emotional stimulation. This stimulation was carried out through an own-design audiovisual database that contained the same number of videos with content classified as positive and negative. The analysis of the data was developed taking into account two experimental approaches, one subject-dependent (SD) and another subject-independent (SI). The results obtained by SD approximation allowed us to elaborate a computational model based on the electroencephalographic (EEG) signal, achieving a precision of 0.989 (±0.013) according to f1-score. The model is based on a 12-second trial window, the non-linear method called wavelet packets for feature extraction, 20 pairs of frequency-location features distributed along much of the cerebral cortex and in the range of 8 to 45 Hz in the EEG spectrum, and the quadratic discriminant analysis and k-nearest neighbors classifiers. On the other hand, in the signal coming from the peripheral nervous system, specific response patterns were found for each emotional category, suggesting that the dimension of valence influences the response of the emotional somatic component. However, taking body response into account did not improve the accuracy of our computational model of recognition of positive and negative emotions; furthermore, the results found do not allow us, for the time being, to make inferences about the physiology of emotions. At the neurobiological level, patterns of inter-hemispheric asymmetry as well as rostro-caudal asymmetry suggest the existence of a neuronal

circuit of emotional valence processing. However, in order to define this circuit precisely and to provide more evidence to the mechanism of action of the dimension of emotional valence, it would be necessary to continue with the studies of the relationships between the different highlighted areas and frequencies. The results obtained by the computational model based on the EEG signal proposed in this doctoral thesis, motivate the continuity of the study of emotions based on the dimensional model, with the objective of demonstrating the validity and reproducibility of the model proposed in real time, and in order to elaborate a theory that gathers the pathway and mechanisms of action of the dimension of emotional valence on both cerebral and corporal components.

Resumen

Las emociones son un proceso clave en la evolución de las especies y en concreto en el desarrollo del ser humano. Influyen en la gran parte de los procesos neuronales que tienen lugar en nuestro día a día, desde la toma de decisiones, la comunicación y relaciones sociales, la atención selectiva, el aprendizaje y la memoria. Lograr entender su fisiología y neurobiología es un gran reto, aún sin respuesta, que lleva planteándose desde la época grecorromana. La gran cantidad de aplicaciones desde la clínica, para el diagnóstico y tratamiento de los trastornos del estado de ánimo, hasta la mejora de las interacciones cerebro-computadora aplicable tanto en pacientes como en individuos sanos, es inimaginable; de modo que conseguir dar con un sistema capaz de reconocer emociones en tiempo real es el santo grial de la neurociencia afectiva hoy en día. Sin embrago, la falta de un modelo teórico que defina el propio término, así como sus componentes primarios y mecanismos de acción, hace que exista una gran variabilidad entre los resultados y modelos computacionales que tratan de resolver la ecuación. De cara a poder establecer un modelo de clasificación de emociones en tiempo-real es necesario fijar una serie de parámetros previos, como el modelo emocional a seguir, el tiempo de ventana óptimo para extraer las características que codifican la información emocional, el método de extracción de dichas características, cuántas y cuáles son las características que representan el procesamiento de la información emocional y el algoritmo adecuado para clasificar este tipo de información y señal. Basándonos en el modelo dimensional de las emociones, en concreto en la dimensión de la valencia que caracteriza el grado positivo o negativo de un estímulo generando respuestas de acercamiento o rechazo, respectivamente; hemos tratado de especificar los parámetros necesarios para desarrollar un modelo computacional que nos permita reconocer emociones en la escala de la valencia emocional enfocado a aplicaciones en tiempo real. Para ello hemos analizado la señal electroencefalografica, electrocardiográfica y la temperatura de la piel, de 24 voluntarios durante la estimulación emocional. Dicha estimulación se llevó a cabo a través de una base de datos audiovisual de diseño propio que contenía el mismo número de vídeos de contenido catalogado como positivo y negativo. El análisis de los datos se desarrolló teniendo en cuenta dos aproximaciones experimentales, una sujeto-dependiente (SD) y otra sujeto-independiente (SI). Los resultados obtenidos mediante la aproximación SD nos permitieron elaborar un modelo computacional basado en la señal de electroencefalografía, logrando una precisión de 0.989 (±0.013) según el f1-score. El modelo se basa en una ventana de trial de 12 segundos de duración, el método no-lineal denominado wavelet packets para la extracción de características, 20 pares de características de localización-frecuencia distribuidas a lo largo de gran parte de la corteza cerebral y en el rango de 8 a 45 Hz en el espectro de la señal de EEG, y en los clasificadores quadratic discriminant analysis y k-nearest neighbors. Por otro lado, en la señal procedente del sistema nervioso periférico, se encontraron patrones de respuesta específicos para cada categoría emocional, sugiriendo que la dimensión de la valencia influye en la respuesta del componente somático emocional. Sin embargo, tener en cuenta la respuesta corporal no mejoraba la precisión de nuestro modelo computacional de reconocimiento de

emociones positivas y negativas; además, los resultados hallados no nos permiten, por el momento, hacer inferencias acerca de la fisiología de las emociones. A nivel de la neurobiología de las emociones, patrones de asimetría inter-hemisférica, así como asimetría rostro-caudal sugieren la existencia de un circuito neuronal de procesamiento de la valencia emocional. Sin embargo, para poder definir dicho circuito con precisión sería necesario continuar con los estudios de las relaciones de las distintas áreas y frecuencias resaltadas, para poder aportar más evidencias al mecanismo de acción de la dimensión de la valencia emocional. Los resultados obtenidos por el modelo computacional basado en la señal de EEG propuesto en la presente tesis doctoral, motivan la continuidad del estudio de las emociones basado en el modelo dimensional, con el objetivo de demostrar la validez y reproducibilidad del modelo propuesto en tiempo-real y para poder elaborar una teoría que recoja la vía y mecanismos de acción tanto cerebrales como corporales de la dimensión de la valencia emocional.

1. Introduction

1.1. General facts about Emotions

1.1.1. History and Models of Emotions

The brain is a machine designed to process information and the nervous system is nothing more than a set of predispositions to react in a determined way to specific characteristics of the environment [1]. In this context, emotions can be understood as a complex system designed to guide our behavior and learning, moving away from those interactions with the environment that may represent a danger to our survival and approaching or tempting the approach to those that provide a benefit to it. Just as the sense of taste separates us from the poison through its bitter taste and makes us eat fruit because of its sweet taste; the emotional system will make us cautious in a dark room when experiencing fear and feeling joy when seeing a loved one.

The two main strands of thought, prior to the 'emotional stage', come from the Stoics and the Christian philosophers. On the one hand, the philosophy of the Stoics preached the dominion and control of passions, which disturbed life, through the use of reason. They actually believed that passions were diseases of the soul [2], [3]. After the fall of the Greco-Roman Empire, during which Stoicism was established, came the Christian era and with it a change of thought regarding Stoic passions brought by the philosophers Augustine of Hippo [4] and Thomas Aquinas [5]. Yet they agreed with the Stoic version that passions were violent forces that could conflict with reason and lead a person into sin; they did not coincide with the fact of completely eliminating them from the mind, since in the Christian religion it is of the utmost importance to know how to distinguish passionate disturbances and desires of the soul, such as lust, and those virtuous affections, such as love and compassion, in order to be able to avoid the former and cultivate the latter. After the Christian era, in the 18th century, writings on *passions* and *affections* proliferated, offering new ideas and theories, but the use of the terms was maintained. The term *passions* applied to those ‘evil propensities', while *affections* referred to 'virtuous propensities' [6].

In 1570, the term *emotion* was adapted from the French word ‘émouvoir’ (translated as "excite/arouse") and used to describe physical disturbances or body movements denoting inner passions or affects (Online Etymology Dictionary. © 2001-2019 Douglas Harper). It was not until the early 19th century that the philosopher Thomas Brown, considered as the father of emotions, gave them a new sense that has prevailed to this day. Emotions became a distinct theoretical psychological category in the science of mind, replacing and coining concepts such as appetites, passions, feelings and affections, used by earlier philosophers [7]. Moreover, even though he defended that elaborating a definition of the term was complex, and he was not mistaken, he ventured to propose one [8]:

“*Perhaps, if any definition of them be possible, they may be defined to be vivid feelings, arising immediately from the consideration of objects, perceived, or remembered, or imagined, or from other prior emotions*.” *- Thomas Brown -*

At the same time, the philosopher Christian Bell also proposed a definition for the term, which similarly endures to the present day. Bell proposed that emotions are certain changes in the mind that can become visible through external signs, such as facial expressions, body movements or gestures, and internal signs, referring specifically to the heart and lungs [9]. From his theory arose the basis that emotions are mental states that necessarily have a bodily expression. Both Brown and Bell agreed that emotion was something of the mind, yet they differed as to whether their constituents were initially mental or bodily. This dissociation body-mind or heart-brain has generated debate and discord since then and even today there is no clear consensus, either on the definition of the term or the specification of its components.

Influenced by Brown and Bell, authors Charles Darwin and William James, English and American, respectively, were the first to try to elaborate a definition of the term and postulate a theoretical model. In 1872, Darwin published his work on the theory of evolution focused on emotions, '*The expression of the emotions in man and animals*' [10]. In it he defended three basic principles, emotional expressions are (1) evolutionary, (2) innate and (3) have an important communicative function. His theory influenced the study of emotions of the next century; mainly two of his concepts exposed on his first principle, the *Serviceable Habits.* The first idea maintained proposed that emotional expressions are inherited from our ancestors, and therefore human and animal emotions are homologous (*Figure 1*). And second, there are a number of fundamental emotions present between species and cultures, specifically, Darwin proposed six: sadness, joy, anger, surprise, disgust and fear.

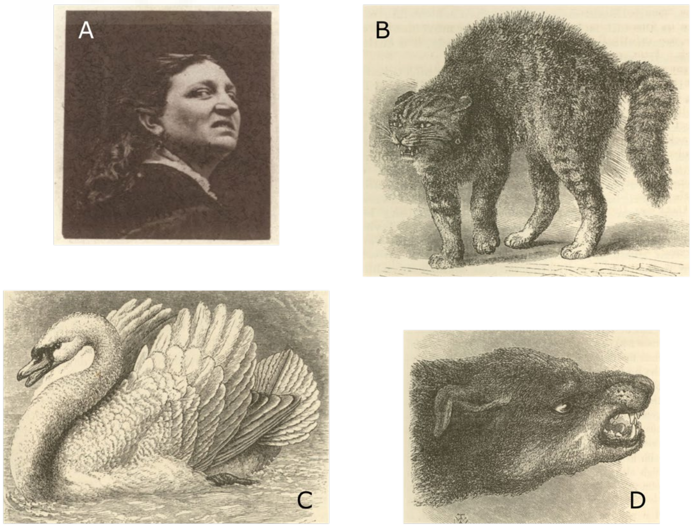

Figure 1. Darwin used drawings and photographs of animals and humans to show the similarity of emotional expressions between species. This figure shows the expression of anger of four different species: (A) human, (B) cat, (C) swan and (D) dog.
From: *John van Wyhe, ed. 2002-. The Complete Work of Charles Darwin Online (http://darwin-online.org.uk/)*

Traditionally, it was thought that emotion arose after mental perception and only after the experience of mental affection (the emotion), the corporal expressions of the same were produced. Contrary, in 1884, James proposed the hypothesis that body changes (muscles, skin, glands, heart and other viscera) occurred directly after the mental perception of the excitatory or emotional stimulus, and that emotion was really the feeling of those body changes [1]. He defended that feeling does not come before action, i.e. if a bear appears, the first reaction would be to tremble or run, and after that, fear would be experienced, in this order and not the other way around. However, emotion does not exist in any case unless both mental perception and bodily changes occur. A year later, and totally independently, the Danish Carl Lange proposed an emotional model very similar to that of the American [11]. Because of the parallelism between the two authors, the idea of that emotions are the experimentation of physiological response to certain stimuli, is known as the James-Lange theory. The theory was innovative in that it called for a change in the order of events that take place in the emotional process; however, it was also harshly criticized. Its main counterarguments were: (1) The response of the autonomic nervous system is not specific to the type of emotion. (2) Artificial induction of physical arousal does not produce real emotions. (3) The disconnection between the peripheral system and the central nervous system does not abolish emotions [12].

The pioneers Darwin and James-Lange marked the basis that emotions are universal and innate mental expressions associated with specific bodily actions or gestures. From them, many other authors got inspired and contributed to the development of new ideas and theories. However, to this day no consensus or universal theory has been reached that demonstrated the origin, structure and functioning of emotions.

Accordingly to the origin of emotions, there are two main currents, the Evolutionary Psychology and the Social or Psychological Constructionism [13]. Proponents of evolutionary theory argue that universal and innate emotions (known as primaries) have evolved to cope with the problems we face and therefore imply an inter-species biological architecture. Furthermore, they assume that emotional responses in the brain and body necessarily go hand in hand. On the other hand, constructionist authors argue that emotions are constructed as a consequence of high level learning and cognitive processes as a result of social or psychological interactions, that is, they are not innate processes but acquired processes that only involve the brain [14], [15], [16]. However, evolutionary psychology seems to be widely accepted, as there is more evidence that corroborate it [13], such as the existence of non-primary emotions in other non-primate species [17], [18], thus demonstrating the evolutionary origin of emotions.

Once the possible origin of emotions has been specified, another point to discuss is their functional structure, i.e. how they are organized and classified. Although each theorist proposes a different vision, there are two main models of emotions: the theory of discrete emotions and the dimensional model of emotions. Regardless of its origin, the debate now focuses on what is the basis of emotions, what is their basic unit? Are these basic components or irreducible emotional elements a set of discrete emotional categories or are they dimensional emotional components? [19], [20].

1.1.1.1. Discrete Model of Emotions

Darwin first proposed the idea that there are a number of innate emotions that are universal and shared by different human cultures because we have inherited them from our animal ancestors. This premise served as the basis for the so-called discrete emotion theory, supported by authors such as Silvan Tomkins [21], [22], Paul Ekman [23], Carroll Izard [24], [25], and Jaak Panksepp [26]. They defend the existence of a series of basic, innate and universal emotions, but nevertheless disagree on how many and what these emotions are (*Table 1*).

Table 1. Compilation carried out by Ortony et al. in 1990 [34], of the lists of basic emotions considered as such by the most relevant authors in the discrete theory of emotions.

Table 1
A Selection of Lists of "Basic" Emotions

Reference	Fundamental emotion	Basis for inclusion
Arnold (1960)	Anger, aversion, courage, dejection, desire, despair, fear, hate, hope, love, sadness	Relation to action tendencies
Ekman, Friesen, & Ellsworth (1982)	Anger, disgust, fear, joy, sadness, surprise	Universal facial expressions
Frijda (personal communication, September 8, 1986)	Desire, happiness, interest, surprise, wonder, sorrow	Forms of action readiness
Gray (1982)	Rage and terror, anxiety, joy	Hardwired
Izard (1971)	Anger, contempt, disgust, distress, fear, guilt, interest, joy, shame, surprise	Hardwired
James (1884)	Fear, grief, love, rage	Bodily involvement
McDougall (1926)	Anger, disgust, elation, fear, subjection, tender-emotion, wonder	Relation to instincts
Mowrer (1960)	Pain, pleasure	Unlearned emotional states
Oatley & Johnson-Laird (1987)	Anger, disgust, anxiety, happiness, sadness	Do not require propositional content
Panksepp (1982)	Expectancy, fear, rage, panic	Hardwired
Plutchik (1980)	Acceptance, anger, anticipation, disgust, joy, fear, sadness, surprise	Relation to adaptive biological processes
Tomkins (1984)	Anger, interest, contempt, disgust, distress, fear, joy, shame, surprise	Density of neural firing
Watson (1930)	Fear, love, rage	Hardwired
Weiner & Graham (1984)	Happiness, sadness	Attribution independent

Note. Not all the theorists represented in this table are equally strong advocates of the idea of basic emotions. For some it is a crucial notion (e.g., Izard, 1977; Panksepp, 1982; Plutchik, 1980; Tomkins, 1984), whereas for others it is of peripheral interest only, and their discussions of basic emotions are hedged (e.g., Mowrer, 1960; Weiner & Graham, 1984).

Authors who support the theory of discrete emotions basically rely on two notions. First, basic emotions are biologically primitive. This idea would explain the fact that primary emotions are shared by different human cultures and even between species; and on the contrary secondary emotions, constructed as a result of the mixture of primary emotions, are not shared among the named populations. At this point it is worth thinking that these primary emotions, have their own representative characteristics, such as their own bodily representation [23], [27], [28], and would be codified in specific and differentiable neurophysiological and anatomical circuits [29], [30], which, moreover, can be found in all mammals and perhaps even in other vertebrates [31], [32]. This concept stems from the belief that basic emotions are an evolutionary necessity for survival. Second, emotions are psychologically primitives, i.e. there is a limited number of basic psychological concepts, primary emotions, that in combination construct the rest of the emotional spectrum, secondary emotions. Although there is disparity between authors as to which are those basic emotions, almost all agree on four emotions: anger, happiness, sadness and fear. In addition, it should be noted that between authors often refer to the same emotion, but with different tag, such as anger-rage, fear-anxiety or happiness-joy-elation.

Ekman resumes the concept of basic emotions as that when the term *basic* is used we are accepting the fact that there are a number of emotions, that differ one from another [28]. Moreover, emotions evolve necessarily to deal with changing life essential tasks for our survival. And finally, we assume that basic emotions may combine to form more complex emotions. If emotions evolve in truth, to deal with fundamental life tasks, then there must be physiological changes as a reflex of them for preparing the organism to react or change its behavior.

Several studies have tried to find the brain sources that encode emotions, since, after all, emotions are mediated by neuronal mechanisms. In the meta-analysis carried out by Katherine Vytal and Stephan Hamann [30], they used the activation likelihood estimation method in order to analyze the similarities between the neural substrates that underlie basic emotions in eighty-three neuroimaging studies (based on positron emission tomography (PET) and functional magnetic resonance (fMRI) techniques). They described specific brain regions for five basic emotions: happiness, sadness, fear, anger and disgust. Despite the results, and although the neuronal basis of some emotions have been well defined, no evidence of different brain pathways has been found for all primary emotions and furthermore, the resulting regions were activated for at least two emotional categories, so no specific regions were found as unique for each emotion [33].

Another strong criticism of the theory was made by authors Andrew Ortony and Terence J. Turner [34], who reviewed the theory in detail and concluded that there was no clear evidence that supported the existence of a series of primitive elementary pillars upon which other emotions were built. Suggesting in this way that the vision of basic emotions may not be the best approach to generate progress in the field. Their main criticisms were the lack of consensus among authors to define which and how many are the basic emotions, and the inclusion of other emotional concepts, such as cognitive states of interest [22], [35] and desire [36]. Thus, highlighting the problem of the lack of a criterion that defines the features that are considered as basic in an emotion and even in the definition of the term itself. Their main opposition was whether these emotions are really basic; that is, whether on the one hand the emotion considered as basic is biologically supported and on the other hand, that it cannot be broken down into other emotions or sub-components. Another criticism, suggested by Klaus R. Scherer, was that the universality of emotional expressions or responses is more likely to be due to the existence of basic components of emotions rather than to specific basic emotions [37].

Even today there is not a consensus about how many and which are these primary emotions or the main statements that encode the term *basic*; however, although this theory seems to be surpassed in practice by other theories that have turned out to be more feasible and useful, there is no clear evidence that can discard it or refute others.

1.1.1.2. Dimensional Model of Emotions

The considered as fathers of psychology, Wilhelm M. Wundt and William James, independently developed their own theory of emotion on the new discipline experimental frame. From their primary vision a second big limb for explaining basic units of emotions emerged, the Dimensional Model, also called or considered as the psychological constructionism approach. As explained on the previous section, James proposed a change in the order of the elements that necessarily take place in any emotional episode. The most important idea to highlight from the James' theory of emotions is that emotions are in its essence, automatic somatic reflexes which progress in time to a conscious state [38]. Otherwise, Wundt believed that defining a list of primary emotions is not possible because of the fuzzy bounds and high overlap between them. But, instead he proposed three fundamental properties or dimensions to describe them [39]: valence (pleasure vs displeasure), arousal or intensity of emotion (low/calm vs high/excitation) and tension or dominance (controlled attention vs relaxed attention). The main contradiction between the emotional theories of Wundt and James-Lange was that while the former considered that emotional introspection derived in physiological and behavioral consequences, the latter defended that physiological responses take place first and then the emotion is experienced (*Figure 2*). Both suggestions of the order in which the responses, triggered by the emotional stimulus, take place, were criticized and practically discarded when Cannon-Bard's theory was proposed [12], [40]. The new theory proposed that emotional stimuli have two independent and simultaneous excitatory effects: the feeling of emotion in the brain and the expression of emotion in the autonomic and somatic nervous systems, the body-mind dichotomy.

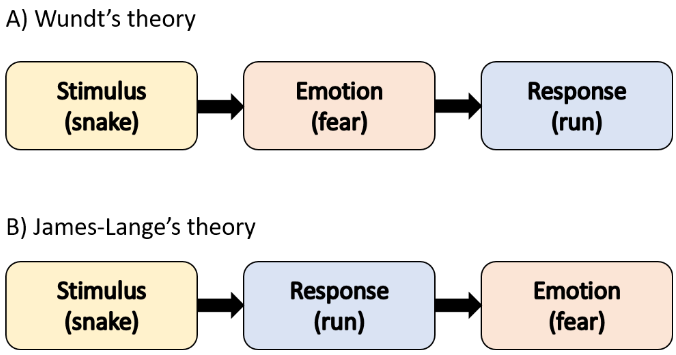

Figure 2. Scheme of the temporal sequence of the components that are part of the emotional episodes according to the theories of Wundt (A) and James-Lange (B).

As with discrete theory, several authors emerged as advocates of dimensional theory, each proposing their own set of basic dimensions and how they interact with each other. Some of the most famous examples (*Figure 3*) are, the circumplex model [41], [42], the Positive Activation- Negative Activation (PANA) model [43], the vector model [44] and Plutchik's model [45]. The conceptual act model [46] is also considered a dimensional theory, as stands for the dualisms between pleasant and unpleasant experiences with some degree of arousal. However, the model proposes three psychological primitives by whom emotions are constructed, the first corresponds to this pleasantness experience which is in line with the main dimensions proposed by other authors, but aggregates memory and controlled attention.

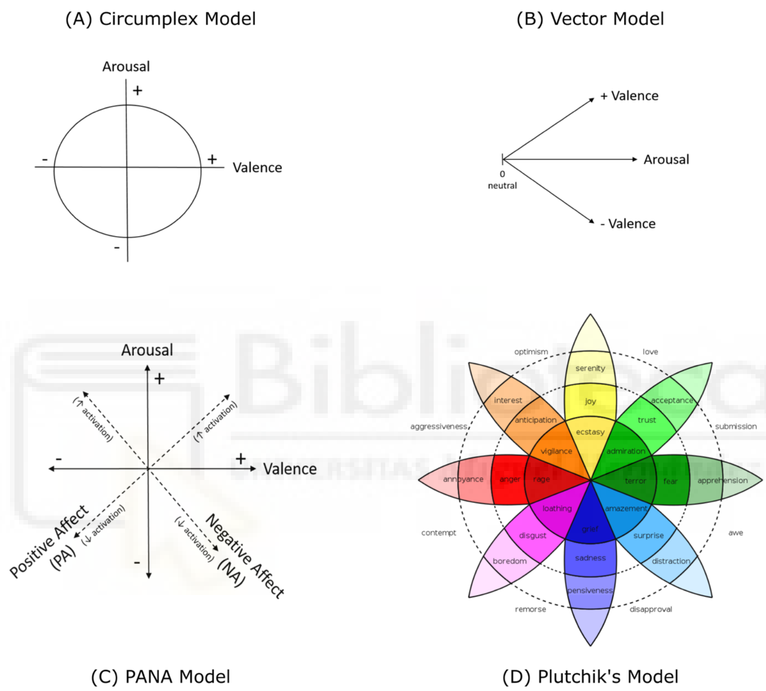

Figure 3. Examples of dimensional theories. (A) The circumplex model is composed by 2 dimensions (valence and arousal) in a circular space. (B) The PANA model suggests that positive and negative affect are two separate systems, valence determine the direction and arousal is linked with the intensity of the affect. (C) The vector model states 2 dimensions, arousal which starts from neutral and valence which determines positive or negative direction. (D) Plutchik's model stands for the existence of eight primary emotion dimensions or four pairs of opposites in a 3D wheel space.

Conversely, in 1938, in his emotional theory, Kurt Lewin [47], defined the term valence as a force that draws us to desirable or valuable stimuli and repels us from those undesirable or invaluable. From this point of view derived the sub-branch of the dimensional theory which maintains that motivational systems of approach (survival and pleasure) and withdrawal (escape or flight responses) are activated with the intention of adapting behavior to an emotional stimulus [48], [49], [50]. These theories are based on dual systems, the components of which are encoded in different neuroanatomical substrates. As examples of dual models we have the behavioral activation and behavioral inhibition systems [51], approach and withdrawal systems [52], appetitive and aversive systems [53] and rewarding and punishing states [54]. With time and in view of its practicality, many authors have limited the classification to the two-dimensional space of valence and arousal, also given the difficulty in distinguishing arousal and dominance [41]. However, there is still no consensus as to which and how many are the basic emotional dimensions [55]. In addition, one of the main criticisms of the theory is the uncertainty as to whether the valence dimension describes the intrinsic emotional property of the stimulus, or instead, it punctuates the subjective feeling of the emotion. The same goes for the arousal, does it describe the intensity of feeling or the body arousal? Is it mediated by a particular neuronal structure or is it rather the general activation state of the system? [56].

Lastly, some authors have proposed that discrete and dimensional theories are not incompatible and that in a certain way both could be measuring the same thing, but simply differ in their labeling (*Figure 4*). In fact, some contemporary authors combine theories trying to perform a best modeling of emotions [57], [58], as any of the presented models is incompatible with the others and none has so far received unequivocal evidence of its veracity to the exclusion of other theories.

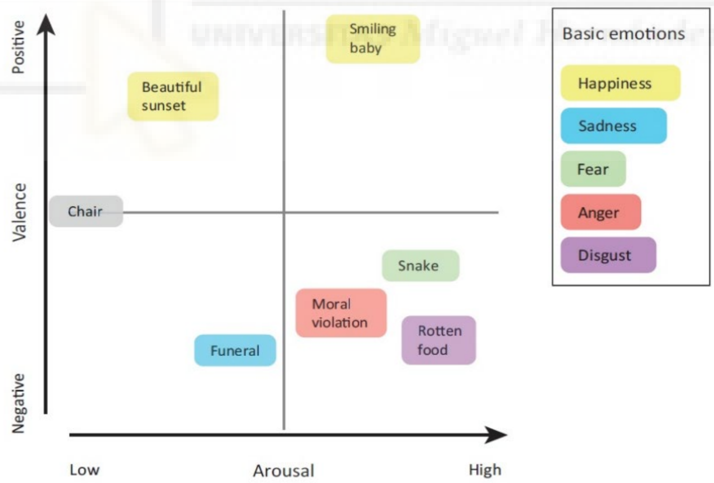

Figure 4. Representation of basic emotions in the space of dimensional theory. From Hamann, 2012 [121].

1.1.1.3. Other Theories

In conjunction with the two main models of emotion, other authors have focus on different emotional factors or features in order to develop new theories. In this section we will name some of the most relevant alternative theories, such as the somatic marker hypothesis of Antonio Damasio and the appraisal model of emotions by Magda Arnold and Richard Lazarus.

Proposed by Arnold [36] and continued by authors as Lazarus [59], [60], Nico H. Frijda [61] and Scherer [62], the appraisal model of emotions or cognitive appraisal theory suggests that the first step in the emotional process is an appraisal of the situation, i.e. the emotion emerges from the evaluation of events. Therefore, explaining the emotional response variability across individuals in front of a specific stimulus, as they arise from people's interpretations. This initial estimation induces the emotional process itself and triggers the appropriate response (physiological and psychological) for well-being. One relevant branch of the appraisal theories is the constructivism view of emotions [63], which is in line with the appraisal cognitive theories in the fact that emotions are constructions built based on subjective interpretations of the environment. However, in the case of social or psychological constructivism theory, emotions are social constructions or brief adaptable social roles. From this view, emotions are an indefinite number that can be adapted to every social situation. They are form by two primary elements, a biological system and a sociocultural system. As another sub-branch of the appraisal theory, the author Scherer proposed two types of emotions, the utilitarian and the aesthetic. The first would be those necessary for our well-being and therefore generate changes in our immediate behavior, such as joy and sadness. Otherwise, aesthetics as fascination and harmony, would not be vital, and would be produced when faced stimuli such as art and music.

In 1962, authors Stanley Schachter and Jerome E. Singer carried out an experiment in which, causing physical excitement through adrenaline injections, they induced joy or sadness depending on the mood of the subject of study [64]. Like James, Schachter equates emotion with the emotional experience or feeling. He proposed that physical arousal takes place first, it is evaluated cognitively, and thus give rise to the emotion. However, one of its main critics demonstrated that cognition is not necessary for affection [65], [66]. Faced with this new criticism, the authors who supported the theory of emotion evaluation conceived other solutions (e.g., [35], [60], [67], [68], [62]). They pointed out that certainly a conscious cognitive process was not necessary to arouse emotions, but they still held the idea that cognition, an unconscious or automatic, must precede emotion even before the bodily response takes place (ej. [36]). In addition, appraisal theorists first presented the notion of intra- and inter-subject variability arguing that emotion evaluation is subjective [69].

Leaving aside the appraisal theory, from the precursor theories of Walle J.H. Nauta [70] and Karl Pribam [71], and inspired by James-Lange theory, Damasio developed its own theory of emotions, known as the somatic marker hypothesis [72], [73]. He defended that there are a series of somatic markers that trigger pre-established responses to certain situations, to guide our behavior and decisions quickly, based on the cost-benefit of the action or result. Markers would influence the response process at both the body and brain levels, and this influence may take place consciously or unconsciously. On the other hand, the term *somatic* refers to the musculoskeletal components, visceral and internal milieu, which confer the response or body state, which can either appear in the body or only in body representation at brain level. One of the relevant facts of the hypothesis is that it proposes that emotions emerge from bodily sensations, taking up again the idea of James. To demonstrate his hypothesis, Damasio was based on the performance of the Iowa Gambling Task [74], in either healthy individuals and in individuals with frontal cortex orbital damage, which lack the markers that will guide the performance for future reward or punishment outcomes. However, other authors have criticized the ambiguity of the study, since its result may have multiple interpretations and not necessarily demonstrate the existence of a system of somatic markers [75], [76]. However, one thing is clear, the rational part of the emotion has been demonstrated by the studies described in patients with cortical damage, especially in the prefrontal cortex (see [73] for a review).

As last work to emphasize, Rafael A. Calvo and Sidney D'Mello [77] made an interesting classification on emotions, based on which affective principle other authors have compared emotions: Darwin-expressions, James-embodiment, Arnold-cognitivism, James R. Averill-social constructs, the affective neuroscience view, James A. Russell-core affect.

As we can see, there are many different theories that try to explain the physiological and psychological basis of emotions, depending on what is considered the basic component(s) of the emotion. However, despite the controversy over the number and qualities of these basic components that must be given in every emotional process, and in the classification of emotions, theorists agree that an emotion has quantity (intensity) and quality (positive/negative valence) [78].

Once the origin and primary functional components of the emotions have been analyzed, it is time to study the events that take place during the emotion and their temporal order. All this will lead us to be able to outline a definition of the term to answer the question: What is an emotion?

1.1.2. The Definition of Emotion and Affect

Emotional processes and states are complex and can be analyzed from multiple points of view, complicating the existence of a common and consensual definition that encompasses the whole picture. The problem is not the lack of a definition of the term *emotion*, but the large number of definitions that exist [79], [80]. Authors Paul R. Kleinginna and Anne M. Kleinginna, tried to synthesize the definition of emotion based on all the existing ones to date [81]. They compiled and analyzed a total of 92 definitions and 9 skeptical statements, trying to identify those concepts common to all authors and therefore relevant to elaborating the definition of emotion. Finally, they proposed a definition:

"*Emotion is a complex set of interactions among subjective and objective factors, mediated by neural/hormonal systems, which can (a) give rise to affective experiences such as feelings of arousal, pleasure/displeasure; (b) generate cognitive processes such as emotionally relevant perceptual effects, appraisals, labeling processes; (c) activate widespread physiological adjustments to the arousing conditions; and (d) lead to behavior that is often, but not always, expressive, goal-directed, and adaptive*". *- Paul R. Kleinginna and Anne M. Kleinginna -*

However, one of their conclusions was that it is not known with certainty how many types of emotions or affections (set of emotions, feelings and moods) exist, not even the clear difference or overlap that may exist between them [82].

In order to give a definition of the term *emotion*, many authors rely on establishing a series of components that they consider basic to the emotional process (for a more detailed review see [78]). Carroll Izard proposed three emotional components: a neuronal circuit, a response system and a feeling; which regulate cognition and action [79]. The component process model proposes that the emotions have five principal components that coordinate and synchronize to give rise to the process of emotion: cognitive (assessment, estimation, appreciation), neurophysiological (body/ arousal symptoms), motivational (actions), motor expression (facial and vocal expressions) and subjective feeling/ emotional experience [37].

Although there is no consensus on the number of components basic for the emotional episode, it seems clear that the components correspond to the functions of (1) appraisal, (2) stimulus monitoring, (3) response preparation and (4) action or response. In order for an emotion to take place, all the components must be given, thus differentiating the emotion from the rest of affective phenomena which would not involve all the components. Moreover, emotions are differentiated from the rest of affective phenomena (feelings, moods and affect) based on the degree of intensity with which its characteristics occur, such as duration, appraisal, intensity or impact on behavior [83]. For example, *emotion* would be distinguished from *mood* on the basis of three components: duration (emotion = short; mood = long), intensity (emotion = high; mood = low), and the presence (emotion) or absence (mood) of a specific target. In general, emotions are considered to be short-lived affective phenomena that always involve self-regulatory responses (changes at the physiological, motor and cognitive level), in order to ensure an efficient, flexible and coordinated goal-behavioral response [84], [85]. In this way, emotions have a beginning and an end. Ekman situates the temporal momentum of the emotion between reflexes (last less than 500ms and start 100ms from the onset of the stimulus [86]) and moods, with a duration between 0.5 and 4 seconds [87]. However, their duration is still an unknown [88].

The concept of *feeling* has been defined as the subjective cognitive experience of emotion [24]. Following this reasoning, the contemporary author Damasio proposes that feelings are defined as the mental representation of the physiological changes that occur during the emotional process, i.e., feelings would be the brain's interpretation of emotions [89], [90].

"*We are not thinking machines that feel; rather, we are feeling machines that think*". - *A. Damasio* -

Damasio defended that emotions are action programs activated by external stimuli (perceived or remembered), automatic, unconscious and innate that try to maintain or restore the homeostatic balance. The *impulses* or *instincts*, which he also considered to be a program of action, would respond to physiological needs (e.g. hunger, thirst, libido). Both emotions and instincts can arouse feelings. Moreover, unlike other authors, Damasio not only excludes the conscious cognitive component from the definition of emotion, but considers it a consequence of it. At this point, it is important to distinguish between emotional feelings and body sensations as pain, thirst or nervousness.

Generally, *moods* are considered to be sustained diffuse affective states, which promote certain feelings or emotions, thus affecting a person's behavior. Their apparent cause is not known with certainty, they have low intensity and generally long duration (hours and even days). They have been considered as the extended version of feelings [39].

One thing that is clear to philosophers and psychologists alike is that emotions are intentional, that is, they are linked and directed at a stimulus, which can be an object (a painting), an organism (a cat), a natural phenomenon (a storm), our own behavior or that of others (a commentary), or a memory or thought [91]. This premise comes from Darwin's vision that the functionality of emotions is to prepare adaptive responses of our behavior to new demands or stimuli from the environment. According to Scherer, emotion will only occur when there are those stimuli that really concern the individual, that is, there will be no emotional response to something or someone that is not relevant, what he called *appraisal driven*. He proposed two types of appraisal, depending on whether the stimulus is assessed by taking into account the needs and objectives of the moment, extrinsic; or by taking into account genetic or learned preferences, intrinsic. From this idea emerges another source of controversy, which is what kind of stimuli generate an emotional response and how they are classified or differentiated from each other; however, in this doctoral thesis we are not going to focus on this question.

Another point that has been taken into account is whether we can have an emotion but not feel it. Authors such as Scherer [83] and Kevin Mulligan [88], argue that the feeling is part of the process of emotion, as is the bodily response (facial gestures, changes in tone of voice and changes mediated through the autonomic nervous system (ANS)) that accompanies it. However, it can be noted that feeling occurs when one is aware that something is taking place, such as a tactile perception or an emotion [92].

In sum, the fact that there is not yet a commonly accepted definition of the term emotion, contributes negatively to the investigation around this phenomenon, preventing the comparison of studies, contributing to the variability and non-reproducibility of the results and generating endless debates. This lack of consensus is also accentuated by the overlapping definitions of other terms related to affective phenomena.

1.1.3. Discussion

It is important to point out the evolution that the concept of emotion has had and how it has been seen from its origin as something negative in the human, to the importance that has been gaining in terms of emotional intelligence [93], the need to understand our emotions and those of others in order to have a healthy mind and body.

In this doctoral thesis we will consider the term *emotion* as a set of neural and physiological processes that respond to an external or internal stimulus (memories, thoughts or images that come to mind), trying to adapt to it and therefore generate a change in behavior that ensures or benefits survival and reproduction. Moreover, apart from the changes generated in the present behavior, emotion will also induce learning through fixations of the whole event in memory to provide a possible better future response. Let's take as an example a situation of real danger, when while driving we go too fast in a rainy day and the car skid, in the moment we get scared and start to feel fear. The fear generated will make the rest of the way more cautious (change in present behavior), however, even though the danger has passed, the emotion and sensation of fear will continue to persist engraved in our memory.

1.2. The Psychological Part of Emotions: Emotions in the Brain

Already in 1884, one of the first texts that tried to give an explanation to the concept of emotion discussed about the location of emotions in the brain; if there were specialized centers or on the contrary the emotions were the result of the simultaneous activation of the motor and sensory centers or others like them [1]. Since then, attempts have been made to find the neuronal substrates that encode emotions or the primitive components of emotion, attending to the defended emotional theory or simply looking for the brain structures involved in the process. Because the way neuronal substrates involved in emotion processing were studied was through the study of patients with brain damage, the traditional vision has been to associate specific and isolated regions to the different primary functional emotional blocks. However, with the emergence of current neuroimaging techniques, there is more evidence pointing to neural networks rather than specific regions to explain the neuroanatomy of emotions [94], [95], as no specific region in the brain has been found for each emotion [96], on the contrary, there must be a signature or pattern of neuronal activation along different brain nuclei.

The first theory on the cerebral mechanisms of emotions was proposed by authors Walter B. Cannon and Philip Bard [97]. After the performance of studies in cats with induced brain lesions, they concluded that the hypothalamus was the cerebral region in charge of the emotional response and that its function is regulated by more recent evolutionarily neocortical structures. By the same time, James Papez proposed a circuit of emotions based on the thalamus as the regulatory structure that triggers emotions [98]. When the stimulus arrives at the thalamus it diverges into both the thought stream linking upstream regions (cortex), where sensory input become thoughts, perceptions and memories; and to downstream regions (hypothalamus), for the feeling stream, therefore generating the emotions. These conclusions, reflected evidences of different level of regulation, what later would be called the mammalian and rational brains.

Based on previous Cannon-Bard and Papez ideas, in 1949, Paul MacLean proposed a triune architecture of the brain [99], where the three subsets based on evolutionary concepts interplay together to create the emotional experience. The first and more ancient part of the brain corresponding to the striatal complex and the basal ganglia is called the reptilian brain, which Maclean proposed that it is the nuclei of the most primitive emotions (survival and reproduction). Next part in evolution corresponds to the mammalian brain, what he baptized as the limbic system [100], in charge of the augmentation of the primitive emotions of the reptilian brain and the social emotions, nowadays it is still referred as the emotional brain. It is formed by the thalamus, hypothalamus, hippocampus, amygdala, the cingulate cortex and the prefrontal cortex. Lastly, the most evolved brain, the neocortex, responsible for the interface between emotion and cognition, constitutes the last control mechanism, through a top-down regulation of the emotional responses triggered at the mammalian and reptilian brains. These three regions (hindbrain, midbrain and forebrain), though to be implicated in the emotional process, are common for all vertebrates conserving basic circuits but differing on size and complexity. Although the theory had a huge impact in the study of emotions and the term limbic system to refer to the neuroanatomical emotional pathway is still in use nowadays [73], contemporary researchers have demonstrated evidences against the theory (see [101] for a review). First, the limbic system and neocortex only exits in mammals, fact that is not true as similar structures have been observed in birds and reptiles. Second, the theory advocates that structures in the limbic systems does not interfere with cognitive processes. And third, suggested connections and emotional functions have not been found between the proposed structures to form the system.

Depending on the number of systems or circuits considered to exist at the brain level, emotional systems based on their functional neuroanatomy can be classified as follows: single-system, dual-system and multiple-system models [102]. Single-systems models defend that all emotions are generated by a same unique neural system. Authors as Cannon-Bard, Papez, McLean and Mills are examples of single-system models. Attending to the dimensional theoretical models of emotions, the dual-system models defend the existence of approach and withdrawal pathways that triggers emotions which can be divided in this duality. Examples are Schneirla, Rolls and Davidson. Finally, following discrete emotions authors that hold this theory suggest multiple-system models, one for each discrete emotion.

Two facts seem clear among authors. First, emotions try to guide our behavior by involving the emotional systems of attraction or withdrawal, determined by emotional valence and the degree of involvement required for the change in behavior (arousal) [85]. And second, the neuroanatomy of emotions necessarily involves both central and autonomic nervous systems for the whole emotional episode to take place [73], [85].

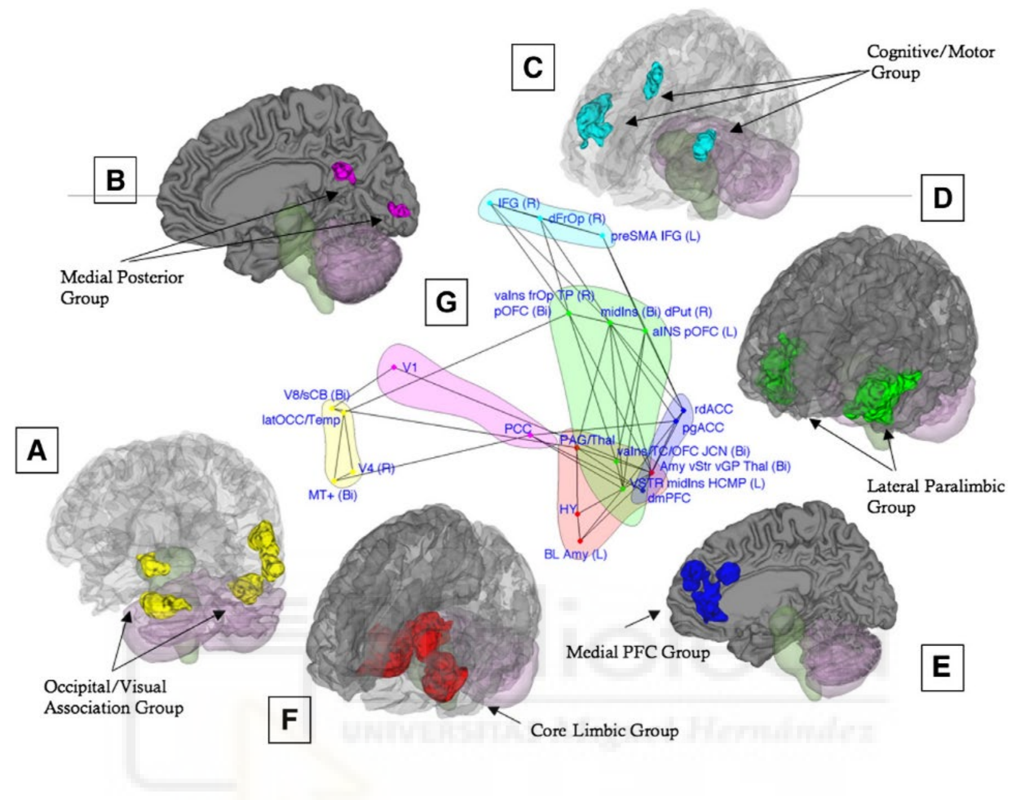

Figure 5. The six emotional brain functional groups resulted from the meta-analysis of Kober et al. [96].

From studies conducted using neuroimaging techniques, six brain functional groups (*Figure 5*) have been identified as been involved in the emotional processing through the meta-analysis conducted by Hedy Kober et al. [96]. Being aware of the variability that exists between studies and authors due to the adopted emotional model, the experimental procedure and the signal analysis methodology used; they compared the results of fMRI studies to date without using emotional labels. In this way, independently of the emotional model used, they looked for the common structures in all of them. The six functional brain groups defined were: (1) lateral occipital/visual association group and (2) the medial posterior group. Both groups are closely structurally interconnected and thought to be implicated in both the visual processing of the emotional stimuli and in the attentional demands of it. (3) The cognitive/motor group, in charge of the intentional action, working memory and response orientation, selection and inhibition; it is associated with the appraisal and labeling of the emotional input and the associated psyco-physical behavioral response. (4) The lateral paralimbic group is thought to play a role in the motivational states, contributing to the valuation of the emotional stimuli and the associated rewards attending to the individual goals. (5) The medial prefrontal cortex group is likely to play a role in both the generation and regulation of emotion. (6) Finally, the core limbic group is thought to participate in the regulation of the autonomic responses related with the emotional stimuli. These defined groups are closely interrelated to each other constituting the emotional network; however, these groups are not specific to emotions, as emotions are thought as events constructed from cognitive, affective, perceptual and motor components.

Although the exact neuronal circuits responsible for the emotional processing are still unknown, agreement exits on several key structures. The amygdala, implicated in the processing of social signals, facial expression and emotional conditioning [103], [104], [105]; above all in fear conditioning [106], [107]. The prefrontal cortex, involved in the processing of the emotional and motivational value of a stimulus [50], [108]. The anterior cingulate cortex is thought as the region where visceral, attentional and emotional information are integrated [109], [85]. It is also evidence that it is implicated in the conscious experience of emotion and in the autonomic arousal representation [110]. Its role is critical in top-down regulation of affective phenomena [111]. Finally, the hypothalamus has also been seen as a key emotional structure, implicated in the processing of reward [112] and primitive behaviors as affective defensive responses, sex and hunger [113], [114]. Regarding the dimensional model of emotions, initially it was believed that the dimensions of arousal and valence were encoded by different neuronal substrates; the amygdala was activated with increases in the arousal scale and different regions of the orbitofrontal cortex were activated for the processing of positive (medial prefrontal cortex) and negative (lateral prefrontal cortex) emotional valence [115], [116]. However, the traditional theory is once more overthrew by recent studies showing the involvement of neural networks rather than individual regions [117], [118], [119]. As a last example of it, Ralph Adolphs et al. [120] studied the processing and recognition of emotions in one patient with widespread brain damage. They concluded that both processes were widely distributed throughout the brain and that different neuronal structures or networks were involved in them, but differing on the type of stimulus (static or dynamic). Finally, due to evidences of co-activation of the same regions in several emotional conditions, the existence of functional networks or circuits, where individual structures can participate in multiple networks and its activation will vary and be modulated by the currently network configuration is adopted instead of the idea of isolated brain regions that link with specific basic emotional components [121].

Despite the variability in studies, approximations and results, most authors and methodologies (studies of brain damaged patients and studies based on neuroimaging technologies) conclude that neural substrates responsible for emotional processes correspond to diverse structures that interact with each other forming emotional neural networks. Moreover, the evidence suggests that there are no conclusive discriminable neural correlates that support the existence of basic emotions [122].

1.2.1. Neuroimaging Techniques for the Study of Emotions

With the growth and advances in technology to record and extract brain signals during the past 20th century, different non-invasive neuroimaging methods have been used to evaluate the theoretical emotional models. Functional brain imaging techniques are mainly based on the detection of two physiological phenomena, the neuronal electrical activity and its metabolic activity, reflected in local hemodynamic changes.

Taking into account the metabolic changes, when a cerebral region increases its activity, it consumes more oxygen, which increases both the levels of oxygenation of arterial blood (due to an increase in blood flow and volume), and the levels of deoxygenated-hemoglobin in venous net. These changes in local blood flow and oxygenation can be detected thanks to the paramagnetic property of the hemoglobin molecule when its iron is not attached to the oxygen molecule. Techniques capable of detecting these changes are functional magnetic resonance imaging (fMRI) [123] and near infrared functional spectroscopy (fNIRS) [124]. Positron emission tomography (PET) also measures metabolic changes, but detects them by administration of short-lived radioactive isotopes; areas with higher radioactivity are associated with greater neuronal activity [125].

For the techniques based on neuronal electrical activity, both magnetoencephalography (MEG) [126] and electroencephalography [127], measure the processes associated with brain magnetic and electrical activity, respectively, through sensors or electrodes positioned on the scalp. It is believed that the measured activity corresponds to the synchronized post-synaptic activity of tens of thousands of cortical pyramidal neurons, which thanks to the length of their dendrites and their distribution parallel to each other can be detected on the surface [128].

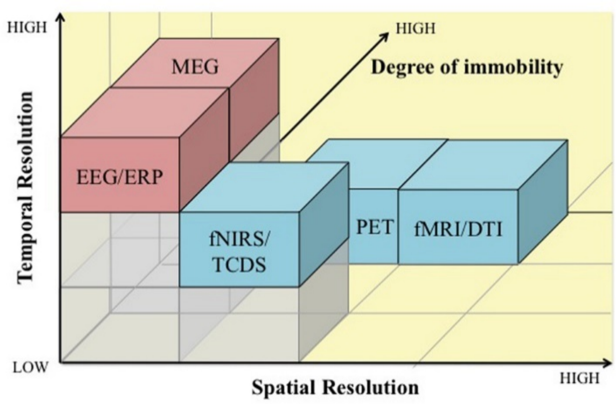

Figure 6. Comparison in the dimensions of spatial resolution, temporal resolution and degree of immobility of the different electrical (red), and metabolic (blue) based neuroimaging techniques. From: Mehta et al. [228].

The study of emotions ideally has to be done in an environment as realistic as possible and that more faithfully reflects the real world, so that the degree of immobility required by the neuroimaging technique used is very relevant. On the other hand, ensuring the veracity of the brain signal measured by limiting its temporal and spatial dimensions is also of paramount importance. Therefore, the ideal technique will be the one that achieves the best balance between the factors of temporal resolution, spatial resolution and the degree of immobility of the subject (*Figure 6*).

Based on its characteristics, for the moment, the EEG is the technique that presents the best conditions for the study of emotions, given its high temporal resolution of the order of milliseconds that allows experiments in real time; its non-invasiveness and portability that allows records to be made in more realistic conditions and outside the clinical or laboratory environment; and its relatively low cost that makes it an affordable technique. However, as a disadvantage, its spatial resolution is not that good as it oscillates in the order of centimeters covering a perimeter of 2 centimeters of diameter around the electrode and about 2 centimeters in deep, which generates difficulty when studying the neurobiology of the neural substrates involved in the processing of emotions. In addition, the inverse problem for EEG source localization increases the handicap in order to draw conclusions about the brain structures that make up the emotional brain network. The inverse problem occurs when trying to find the location of the source generating the signal from among all the tangle of electrical signals, because, the solutions that exist for a single source are infinite [129], [130]. Thus, if we want to study the neuronal sources involved in the processing of emotions, the best technique is fMRI; but if, on the contrary, we want to develop realistic applications that recognize and classify emotions in real time outside the clinical environment, the EEG is the technique par excellence.

The recording of the first human electroencephalogram was first carried out in 1929 by the German neurologist and psychiatrist Hans Berger [127]. Electrodes are placed on the surface of the scalp, which detect and record a small electrical charge, this is amplified and represented in voltage-time coordinates (amplitude and latency, respectively). The neuronal post-synaptic potentials are largely confined in the dendrites and cellular body, lasting between tens or hundreds of milliseconds; these factors allow them to add up in time through synchronization and in space due to cortical architecture (electric fields close to each other and oriented in the same way); thus making possible their detection in distant zones as the scalp. When a post-synaptic potential occurs, electrical currents are generated from the flow of ions through the membrane. The generated intra- and extra- cellular currents flow in opposite directions and their direction will depend on whether the synapse is excitatory or inhibitory. We call source the place where the extracellular current begins, area of positive voltage; and sink the place where the extracellular current flows, area of negative voltage. When there is a current flow between a source and a sink that are separated in space a dipole is generated; these dipoles are the signal generators in the EEG.

Two types of signal can be extracted from the EEG, in the time domain, known as event related potentials (ERPS); and in the frequency domain, the spontaneous electrical activity. ERPs are a set of electrical potentials that represent neuronal responses to specific static events, and therefore are locked in time to them. In order to extract them, it is necessary to average the EEG signal in each stimulus repetition. On the other hand, spontaneous signals are often described in terms of rhythmic activity, classified into frequency bands. The spectral frequency range of the EEG signal corresponding to the brain activity oscillates between 1 and 45 Hz, and is mainly divided into 5 bands: delta (0-4Hz), theta (4-8Hz), alpha (8-14Hz), beta (14-30Hz) and gamma (30-45Hz). The temporal and spatial patterns of the different frequency bands are associated with various brain states or dynamic stimuli. As for the study of emotions in conditions that imitate reality as faithfully as possible, the spontaneous electrical activity of the EEG is the one studied. The main goal of EEG based emotion recognition resides on the achievement of emotion classification in real time. To do that, some objectives have been pursued as the reduction of the number of electrodes to develop more simple and comfortable devices [131]; the definition of the relevant frequency-location patterns [132]; the time window that best reflects the emotional process [133]; and the proper data processing to extract the important information [134], [135], [136].

1.3. The Physiological Part of Emotions

Most emotional theories contemplate a somatic, peripheral or bodily emotional component, to be activated during emotion, which is mediated by the ANS. However, there is disagreement about how many different response patterns exit. The term, ANS, and its divisions based purely on neuroanatomy and not on its functionality, were proposed by Langley at the beginning of the 20th century [137]. The ANS is responsible for regulating involuntary metabolic and bodily activities in a coordinated manner to ensure homeostasis and adaptation of the organism to the changing external environment. At the anatomical level, the ANS does not directly innervate the effector organs, but it is a system of two neurons, the first one is inside the central nervous system (CNS) and the second one is in the so-called autonomic nodes. Depending on the origin of the pre-ganglionic neuron and therefore the location and targets of the post-ganglionic neuron, the two divisions that make up the ANS are distinguished, the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS) (*Figure 8*). At the functional level, global activation of the SNS prepares the body for "fight or flight" responses, increasing heart rate and blood glucose levels, and moving blood primarily from the visceral organs and skin to skeletal muscles. However, the SNS not only acts in "emergency" situations, but also plays a key tonic role in the regulation of the cardiovascular system and other organs, such as the kidneys. The SNS regulates homeostasis and body responses through the direct action of the neurotransmitters noradrenaline and to a lesser extent acetylcholine, on effector tissues; and through the release of steroid hormones, such as adrenaline and noradrenaline, into the bloodstream by the adrenal glands. Many of the actions of the PNS and the SNS are opposed, so that, since the SNS is known as the predominant system in situations of alertness or physical activity, the PNS is believed to mediate in states of calm and safety or rest, mostly regulating the cardiovascular and digestive systems. The neurotransmitter released by parasympathetic postganglionary neurons is always acetylcholine. And, although SNS could be activated in a massive way, no situations or evidence have been found in which the PNS is activated in this way (the revision of the ANS has been based on the book [138]).

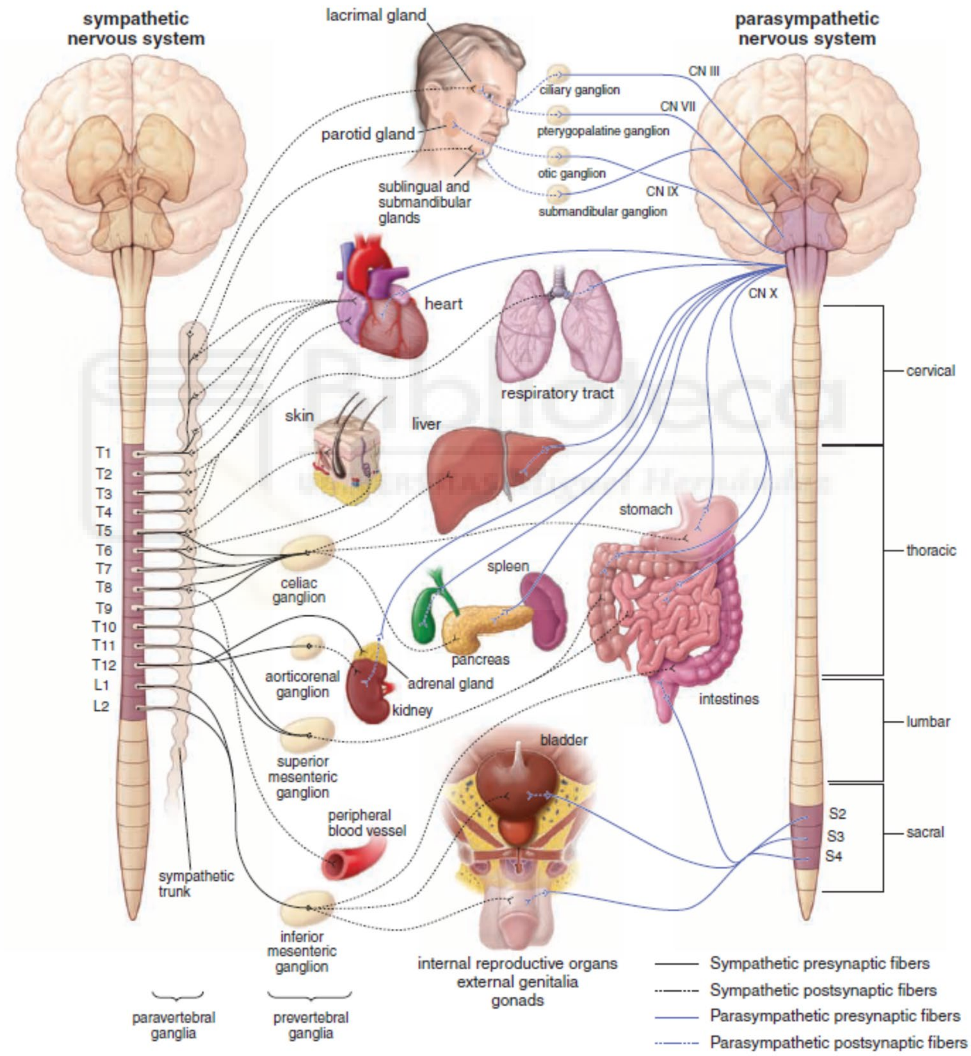

Figure 7. Schema of the anatomy of the PNS and SNS. From [138].

It is traditionally believed that the SNS and the PNS systems regulate action and inaction respectively, i.e., the need to mobilize to meet the demands of survival depending on whether the environment is hostile or favorable. They are thought to be activated in an inhibitory way among themselves, i.e., they are not acting at the same time, one or the other predominates [139]. However, in the last 50 years it has been shown that this view of the ANS is erroneous, each tissue is innervated by both branches of the ANS, but their function is independent of each other [140], [141], and in addition, they do not show a generalized activation pattern, but may act on isolated organs [142]. In general, the SNS and PNS systems serve the same target organs, but the effects on them can be antagonistic (e.g. at the heart pacemaker, the SNS accelerates and the PNS decreases heart rate), complementary (e.g. on salivary glands) or cooperative (e.g. on the reproductive system). On the other hand, some organs, such as the adrenal medulla and the cutaneous effectors (blood vessels, sweat glands and piloerector muscles), only receive sympathetic innervation, so that activity is regulated by increasing or decreasing of the sympathetic tone. In this way, conclusions about the function or role played by the ANS in the emotional process, based on the measurement of a single component or effector of the ANS, may not be considered [143], [144]. Thus, although, the heart rate is the most often reported autonomic measure, in order to come to understand the role of the ANS in emotion, the simultaneous recording and studying of several complementary autonomic effectors would be more accurate [145]. In any case, with the studies carried out to date, it is not clear what is the role that the ANS plays in the emotional process. As happens with the emotional neural networks, if the emotional response is linked to discrete emotions, therefore there should be specific physiological responses for each emotion. Or if, on the contrary, the ANS responses are also divided into valence and arousal dimensions; is there a bivalent response on the valence scale and another on the arousal scale? is the answer a combination of both scales? Or, does the physiological response only obey to a particular scale, valence or arousal?

Evidence has been found that there are specific bodily responses for each discrete emotion, such as facial expressions; in fact, this is the main reason for discrete emotional theories. However, this specificity although it has been demonstrated in some cases (see [146]), it has not been shown in all proposed innate emotions, which calls into question the existence of discrete neurophysiological patterns. On the other hand, according to the dimensional theory, there is also controversy in the results since some authors bet for the existence of patterns in the valence scale according to the activation of the motivational systems of approach and withdrawal [147], [145]; and others give the quality of the intensity of the response to the arousal dimension [148]. It is expected that when withdrawal behaviors are needed, the SNS mediates the responses of increasing the heart rate, the respiratory rate, increase perspiration and produced vasoconstriction at the skin; opposite effects, mediated by the PNS, are expected when approach behaviors occur. However, this positive-negative pattern is not fulfilled in all situations depending on the label of the emotion, that is, stimuli that represent different discrete emotions, but have the same valence value, they do not generate the same autonomic response [145]. Results of parallel studies indicate that there is no distinction based on emotional valence in the physiological response, but that this response is more diffuse and therefore less specific to the type of emotion and only obeys the arousal scale, behaving as a whole or nothing, i.e., activating the response of the ANS, presumably the sympathetic branch, in the presence of high excitation emotional stimuli. Schachter and Singer, in their theory of the undifferentiated arousal, they argue that all emotions necessarily activate the ANS as a preconditioning of the body to ensure a better adaptive response [64]. Despite the expected theoretical response from each branch of the ANS, the role they play in emotions is still controversial. The fact is that it is not clear whether there are specific differences in the different emotional responses at the ANS level [53], [147], [149]. However, reasoning says that because emotions have different objectives they therefore require different bodily responses [143].

Another important point is which is first in the emotional process, the psychological or the physiological component. This fact has been discussed by all authors when trying to elaborate a definition for the term emotion, its components and its temporal sequence. Dirk Hagemann et al. have observed co-occurring activity at cortical and subcortical regions at the time of ANS responses in emotions [148]. Robert W. Levenson also saw the ANS emotional patterns as part of the emotional process and not as a consequence or response to it, contributing actively to the process and helping us to be aware of what is going on, what are we feeling and how to label it [150]. Moreover, it provides us a frame for communicating with others.

Below, we will briefly discuss about the physiological measures most used in the recognition of emotions that in turn have been used in the development of the present doctoral thesis: cardiac activity and skin response. Other body responses such as facial expressions, tone of voice and posture and body language have also been studied and used for the recognition of emotions, although to a lesser extent, as the equipment and systems needed to use these sources of information are more expensive and more difficult to use, as this needs to be done in controlled environments [77].

1.3.1. Electrocardiography

The cardiovascular system is innervated by both divisions of the ANS, the heart receives efferent inputs from both PNS and SNS, while the blood vessels do so only from the sympathetic branch. One of the most informative measures of the ratio between SNS and PNS is the heart rate variability (HRV). HRV is the fluctuation on time at the instantaneous heart rate, i.e. between consecutive heartbeats [151], several measures in time domain, frequency domain, Pointcaré plot measures and geometrical methods could be calculated from the heart rate intervals. HRV measures the continuous influence of both SNS and PNS on heart rate, that could reflect the flexibility and adaptation of the ANS to the internal and external emotional inputs or situational demands, and reflects the ability to adapt to the changing environment. Both parasympathetic and sympathetic division of the ANS innervated the sinoatrial node or primary pacemaker of the heart, by producing inhibitory and excitatory effects on the heart rate, respectively. However, in resting conditions the parasympathetic influence prevails, thus maintaining normal firing rate [152]. In turn, SNS and PNS activity is influenced by the central autonomic network outputs, which are developed in order to adapt the response to internal (visceral) and external (sensory) demands [153]. In sum, both ANS branches contribute to the regulation of the heart rate intervals, however the way in which HRV represent the balance between them is not entirely clear yet. Moreover, HRV is influenced by factors as gender and age [154], and also by external compounds as drugs [155], [156], tobacco [157] and alcohol [158].

In terms of its role in emotion, the same dichotomy between the discrete and dimensional theories exits in the studies regarding HRV for emotion recognition and evidences supporting both theories have been found (e.g. assuming the discrete model [159], [160], [161], and the dimensional model [162], [163]. Although there is evidence in favor of both emotional models, Sylvia D. Kreibig reviewed the literature related to ANS activity in emotions by evaluating the physiological response of different discrete emotions while separating them into two groups depending on whether these emotions corresponded to positive or negative emotions. Results showed that within the dimensional groups there was no common pattern between discrete emotions labeled as positive and negative. Suggesting that cardiac activity does not reflect or is not regulated by the emotional valence scale [145].

There is also controversy as to which are the most informative variables about the state of cardiac activity during emotional processes. However, given that it is not even clear what representations or role each division of the ANS plays in cardiac physiology [164], it is complicated to relate the different parameters to their role in the emotional function. Therefore, research in the area has tried to be more pragmatic, using HRV measures to try to classify different emotional states for future applications, but without focusing too much on their biological significance.

1.3.2. The Skin

The autonomic effects of the skin (blood vessels, sweat glands and piloerector muscles) are only regulated by the sympathetic division, so the skin is a good target to study the involvement of SNS in emotional processes [138].

1.3.2.1. Blood Vessels: Skin Temperature

The skin temperature depends, in general, of two factors: the rate of blood flow (vasocontraction and vasodilation) through it and the temperature, humidity and movement of the surrounding air. Its main function consists on the thermoregulation of the body [165]. The sympathetic innervation and release of norepinephrine leads to vasoconstriction and therefore to a decrease of skin temperature. The skin temperature is not homogeneous in the whole body, temperature can vary at different positions [166], [167]; it used to be higher at the head and trunk and lower at the extremities [168]. At the extremities, changes in skin temperature can be detected more easily at the sole of the foot and palm of the hand and at the end of the digits, where anastomoses are found [168].

As for changes in skin temperature during emotional processes, most authors agree in the association between skin temperature decreases with stressful or threatening situations, increments of skin temperature during positive emotions and no change, in respect with baseline, for cognitive stimuli [169], [170]. Coinciding in this way with the spread theory that says that when the environment is perceived as safe, it is the PNS who is in charge of the normal physiological function. And contrary, when the amygdala is activated in front of a defense response, the SNS takes control. In this process, different hormones are released to the blood stream, among them epinephrine which elicits subcutaneous vasoconstriction, therefore, minimizing the venous blood volume under the skin, preventing the overmuch blood loss in case of getting hurt [171], [172].

Due to new methods of thermal imaging, the skin temperature is gaining importance as an emotional source of information. The typical positions of the thermal sensors are on the hands and face, however in the last years, biosensors place on bracelets have increase their popularity in society due to its comfort. However, the placement of thermistors has been unseated by infrared thermography, mainly due to two advantages. On first place, thermal infrared imaging is not limited to the small surface cover by the electrode, instead it can evaluate large areas of skin. Secondly, it is contact free as it makes the recordings through a camera facing the subject, what results more comfortable for the experimental setup.

1.3.2.2. Galvanic Skin Response

As with skin temperature, skin sweating is also controlled solely by SNS. Changes in sweating cause changes in the electrical characteristics of the skin, known as electrodermal activity. These changes in skin conductance are measurable and when induced by stimuli are known as the galvanic skin response (GSR) [173]. As with temperature, changes in skin conductance differ depending on the area in which it is measured, with the feet, fingers, and shoulders being more reactive [174]. But unlike temperature, the GSR does not depend on external factors, which can be introducing noise into the results. GSR has been used in clinical applications [175], in emotion recognition applications [176], and measuring the workload on mental exercises [177]. Regarding emotions, the GSR response have been associated with the undifferentiated arousal theory, due to increases of GSR response have been observed to take place in both sides of the valence scale [178].

1.3.3. Discussion

For the recognition of emotions, the EEG signal presents a better performance compared to the physiological signals [179]. However, the recording and analysis of physiological signals, especially the measurements of the cardiovascular system and the different types of response in the skin, are easier to record and analyze, as well as having a lower cost and better portability; so they are more accessible for the recognition of emotions in real time outside the clinical or laboratory environments. It is for this reason that efforts in the recognition of emotions based on physiological measures continue, not only in order to develop applications focused on treatments or to improve people's day-to-day interaction with technology, but also to understand the physiology of emotional processes. Although some measures of the emotional response are better or most informative than others, there is no 'gold-standard', but the most effective approach to emotion recognition is the combination of psychological, physiological and behavioral measures [94].

1.4. Emotion Elicitation

Emotions can be elicited by the stimulation of any of the senses or imagination mood induction procedures. Although imagination method has demonstrated good results (e.g. [180]), this type of stimulation is not the most convenient due to it is not able to be controlled under experimental conditions and therefore, the reproduction of the results it is not plausible. The most potent emotion elicitation procedure, over other methods such as imagination, music or positive/negative feedback after tasks, is the use of film or story telling [181]. When stimulating senses, the most studied ones have been audition and vision. Some studies have been conducted through odors [182], flavors [183] and tactile stimulation [184]; but the most development senses in humans are audition and above all vision. Regarding both most studied senses, the main method used for emotion elicitation has been the use of two databases, one containing pictures, the International Affective Picture System (IAPS) [185], and the other one regarding sounds, International Affective Digitized Sounds (IADS) [186]. Both databases in conjunction with the Affective Lexicon of English Words (ANEW) [187] have been developed in order to provide an available standardized set of emotional-stimuli material. The standardization of the emotional stimuli is critical to ensure experimental control and allowing the replication of the results across population samples and researchers. Although, research based on these databases is wide, the kind of information that can be achieve from it, does not reflect accurately the real world and therefore the biological mechanisms that actually are taking place in our daily live. As IAPS and IADS constitute pictures and short duration sounds, as beeps, only brain event-related activity is elicited. This information could be useful in terms of understanding the neural pathway of emotional stimuli evaluation, but it would fail when trying to detect and recognize emotions in a more realistic environment, solving daily problems or in clinical applications. In order to approximate to reality, researchers started using audiovisual stimuli for emotion elicitation. The most commonly used tool for the induction of emotions have been film clips [145]. As right says James J. Gross and Levenson in 1995 [188], films are the best way to elicit emotions experimentally under laboratory conditions, due to its advantages such us dynamism instead of static nature and the high degree of ecological validity. However, the main limitation is that there is not a widely accepted, empirically validated set of emotion-eliciting film stimuli. Different authors have deal with the challenge of developing an emotional-stimuli database such as the Database for Emotion Analysis using Physiological signals (DEAP) [189] or the Emotional Movie Database (EMDB) [190] which have been rated in different emotional scales and therefore, have been validated as emotion-eliciting stimuli, and moreover, they also contained different psychological and physiological recordings contributing to the reproducibility of the results. There exist databases based on the dimensional theory of emotions (DEAP and EMDB) [191], the discrete theory [192] and some trying to mix both models [193], [194]. However, in spite of the attempts to generate standardized and free emotional audiovisual databases, unlike the images or sounds of static databases, the language in which the videos, extracted from films or videos from the Internet, is a limiting factor when it comes to generalize the use of these stimuli. It is for this reason that among the authors who work with different populations, they decide to make their own selection of videos. Furthermore, reproducibility is complicated by the fact that most of the audiovisual fragments are taken from films having relatively long duration, which generates a lot of non-emotional noise, since emotion is not usually present in the whole plot.

Another problem concerning emotional databases is culture, and that is that, although according to evolutionary theories the entire world population is capable of recognizing certain basic emotions, the fact that a stimulus arouses the same emotion or the same value on dimensional scales is unlikely and difficult to measure or secure. The way in which emotions are scored has been also studied [146]. Two main scales are the most used: the Differential Emotions Scale (DES; [195]) and the Self-Assessment Manikin (SAM) for the dimensions of valence, arousal and dominance [196]. However, the problem with scoring emotions is that any score is always subjective.

1.5. Affective Computing

Affective neuroscience is the area of neuroscience dedicated to the study of the neurobiology of emotions, the term was introduced by Panksepp in 1992 [197]. A little over 20 years ago, Rosalind W. Picard, based on the fact that emotions influence many of the mechanisms of rational thought such as decision-making, perception of the environment or learning, proposed that in order to achieve intelligent technology that interacts naturally with the human being, it is necessary to endow them with emotional knowledge, thus giving rise to affective computing [198]. From affective neuroscience, whose main objective is to understand the neurophysiological bases of emotions, more pragmatic branches arise, such as affective computing and affective brain computer interface (aBCI) that try to recognize emotions and respond in the most accurate way to them, in order to achieve a better human-computer interaction, but without taking too much into account the biological sense [199]. The new branches of study seek to develop systems capable of recognizing, interpreting and responding to human emotions. The field of affective computing is highly interdisciplinary using tools from several research areas as the concepts, theories and protocols from psychology; the fundaments of brain functioning and signal processing methods from neuroscience; and machine learning and human computer interface algorithms from computer science. The need of including emotional intelligence skills on machine intelligence is ever more present. New generations are growing hand in hand with technology, and as a consequence, a shift on thinking from new computer and technology development either on social and educational abilities is needed. The utilities and improvements of recognizing emotions in real-time by our machines could be unimaginable and full of advantages. Therefore, resolving the equation of human emotion recognition could have a huge impact in our society.

The first targets of BCI devices were focused on assistive applications such as communication [200], locomotion [201], motor restoration through neuroprotheses [202] and environmental control [203]. In the recent years, the growing BCI area leads research through the necessity of improving the human-computer communication in terms of accurate user experience and efficient computer work; and moreover, enlarge the applications towards healthy/ non-disable people. BCIs decode information from brain signals to deduce user intentions, which is suitable with the new aim of offering an answer or feedback based on the user's emotions or instantaneous necessities without the requirement of out express them. Moreover, it is believed that neuroimaging could help to reveal information about unconscious consumers' preferences that cannot be explicitly expressed, which leads to a new born branch that tries to apply aBCI to test product concepts and advertising called neuromarketing [204].

An aBCI system capable of recognizing emotions in real-time requires the accomplishment of several steps [77] (*Figure 9*) as emotion elicitation, data collection and signal preprocessing, feature extraction, feature selection and emotion classification. The different steps are discussed along the present doctoral thesis.

Emotions are a conglomerate of neuronal processes that are difficult to measure both individually and in a coordinated manner; they also have diffuse limits between them and are highly influenced by the subjectivity of each individual [77]. Therefore, finding the desired model of subject-independent emotional classification, i.e. the proper technique selection and combination for each step of the formula for emotion recognition, is the great challenge for computational affective neuroscience nowadays. To the problems related with the subjectivity of each individual, the inter-subject variability, the fact that emotional states are codified by neuronal circuits instead of isolated brain regions, the lack of consensus regarding emotional psychophysiological theories and the incognita of the temporal course of the emotional process; we have to add another factor that must also be taken into account and solved before finding the algorithm that allows the recognition of emotions in real time: the intrinsic variability of the brain. It has been seen that healthy, young brains have greater cerebral variability than older, poor performance brains. What indicates that the cerebral variability is necessary for a young brain for responding with greater rapidity and greater success [205]. This fact has been observed in the EEG signal of the same subject, recorded on different days and under the same stimulus; the EEG signal was different in each measure, suggesting that the intrinsic cerebral variability naturally present in our brains, also influences the processing of emotions [206], [207]. There is a great variability in terms of experimentation and therefore in the biology of emotions, some theories take it into account and try to give an explanation, and others do not. However, constructionist psychological models defend that this variability has to be a main characteristic in any emotional theory that tries to define and explain the functioning of the same [46].

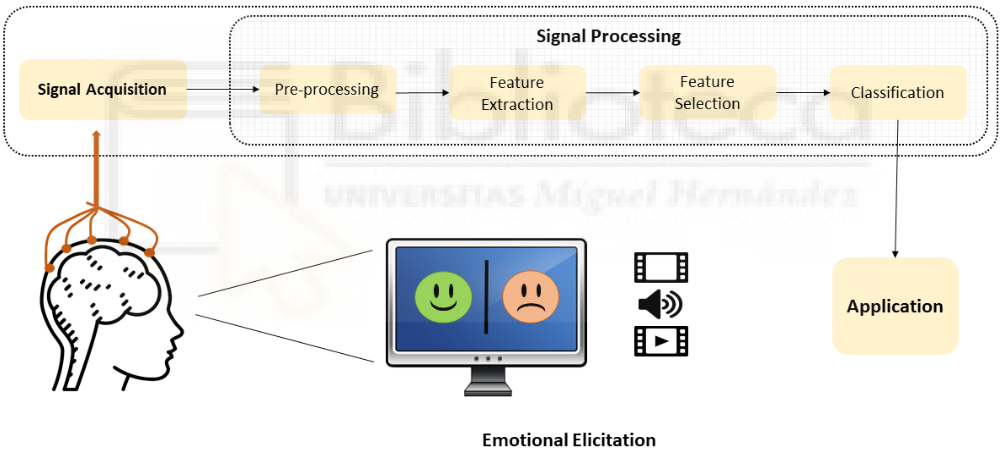

Figure 8. Diagram of the typical procedure of a BCI system, in this case, capable of recognizing emotions.

In addition to the variability provided by the above factors, some authors have emphasized gender differences; it seems that emotional experience and expression are different in men and women [148]. In addition, these facts become even more evident in the association between the ANS and the CNS, suggesting that the response of both systems is influenced or moderated by gender [208], [209], [210]. Therefore, as gender differences are biologically known, differences in parameters relating to emotional responses are expected and have been observed [211], [210]. However, although the differences between genders at the physiological level are clear, there is still no consensus about modeling the gender response to different emotional conditions.

1.6. Research Line

One of the main lines of research of the Neuroprosthesis and Visual Rehabilitation Unit of the Biomedical Neuroengineering Group (NBIO), in which the present doctoral thesis has been carried out, is the development of biomedical technology applied to neurorehabilitation and assistance to disabled people. Its basic and applied research has been related to the design and development of systems that can help improve the cognitive, communicative and physical abilities of people who suffer some type of disability (sensory, motor or visual). In recent years, the laboratory has focused on the analysis of changes in electrophysiological and electrooculographic (EOG) signals [212] in the face of static emotional and cognitive stimuli, finding characteristic brain patterns corresponding to a state of liking or rejection, relying on models of biphasic emotions [213], [214]. These preliminary results have allowed us to lay the foundations for more advanced studies, so now we plan to use dynamic stimuli with the intention of extracting and classifying brain information relevant to emotional processes at the same time as this occurs. This knowledge can be used to contribute to the development of a new generation of brain-computer interfaces.

Our purpose is to clarify the neural mechanisms underlying the experimentation of biphasic primary emotions and to establish the methodological basis for the development of an emotional recognition system in the context of human-computer interactions. We intend to apply this knowledge to socially relevant problems such as assistance to elderly or disabled people or in diseases such as autism spectrum disorder or mood disorders, all framed in social assistance robotics. Therefore, we propose to approach research from a multidisciplinary point of view, using a combination of computational techniques, neuroimaging (electroencephalography, functional magnetic resonance), physiological (electrocardiography, skin temperature) and behavioral (subjective emotional scale), combined with other auxiliary monitoring (eye movement dynamics).

2. Objectives

The main objective of this doctoral thesis is to specify the different parameters necessary to generate a computational model capable of real-time recognition of positive and negative emotions, that is, focused on the valence scale of the dimensional model of emotions, based on EEG and physiological signals.

The specific objectives are:

1. Specify the time window of the EEG signal in which emotions are encoded.
2. Select and characterize the location and frequency parameters of the EEG signal representing the neuronal substrates involved in the processing of positive and negative emotions.
3. Compare the most common feature extraction methods of the EEG signal and specify the most effective one for real-time classification.
4. Compare the most common classifiers in order to determine the one that presents the best performance for real-time emotion classification based on EEG.
5. Study the physiological emotional response of the cardiac and cutaneous systems.
6. Evaluate the contribution of the combination of the CNS and ANS systems in the classification of emotions.

3. Materials and Methods

The following methods correspond to a brief summary of the methods used to carry out the articles that make up this doctoral thesis. The details of these can therefore be found in section *8. Annex: publications*.

3.1. Experimental Procedure

The data set used for the development of this doctoral thesis was obtained from a total of 24 participants (16 men and 8 women). All volunteers were right-handed, between 19 and 37 years old, with normal or corrected vision and hearing, and had no history of neurological or psychiatric disorders. The participants were stimulated by means of an own-design audiovisual database, while their cerebral (EEG) and physiological (ECG and skin temperature) signals were recorded.

The audiovisual database consisted of a total of 14 videos of different emotional content extracted from the internet, divided into two categories based on the emotional valence scale; 7 videos had positive emotional content and the other 7 were of negative emotional content. The length of the videos ranged from 43 to 78 seconds. The audio was instrumental music or Spanish language. The clips were presented randomly and counterbalanced between the subjects, interspersed with a black screen of 30 seconds duration, which indicated the rest time. During the first black screen the signal used as baseline was recorded. During the rest times adjacent to each video, participants were asked to rate their emotional experience on the scales of valence (1 very negative - 9 very positive) and arousal (1 very relaxed - 9 very nervous).

3.2. EEG

The EEG signal was recorded by the NeuroScan system (Compumedics, Charlotte, NC, USA) of 64 Ag-AgCl electrodes, positioned according to the 10/10 positioning system [215], with a sampling frequency of 1000Hz. Offline, the signal was re-referenced to a common reference and filtered between 0.5Hz and 45Hz, using a high-pass filter and a low-pass filter, respectively. The software used for the recording and initial pre-processing of the signal was Curry 7, from the same company, NeuroScan.

Due to the recorded signal could be affected by non-brain electrical signals or artifacts such as muscle movements, blinking and the electrical network (50Hz EU, 60Hz US) [216], these artefacts were removed by selecting the components from the independent component analysis that contained them [217]. The filtering of the artifacts was carried out through the Matlab (The MathWorks Inc.) toolbox called EEGLAB [218]. Despite the elimination of the main artifacts, of the initial 64 electrodes, only 52 were used for the following analyses due to the noise they still presented. Finally, the signal corresponding to each video excerpt was standardized with respect to the baseline by means of a z-score.

3.2.1. Feature Extraction

The resulting signal after pre-processing was segmented in trials from 1 to 12 seconds, forming a total of 12 sets of study according to the size of the trial, in such a way to evaluate the time window needed to detect the emotional process. The spectral power of 6 frequency bands (Delta (1–3 Hz), Theta (4–7 Hz), Alpha (8–13), Beta1 (14–23Hz), Beta2 (24–30Hz) and Gamma (31–44Hz)) was extracted from each electrode and for each time set. To extract the signal features in the frequency domain, two different methods were used in order to compare the results; a traditional linear method based on the Fourier transform, the Welch's method and a method that better addresses the non-linear nature of the EEG, the wavelet packets decomposition method. The spectral signal of the 52 study electrodes was grouped into 13 functional groups: Prefrontal-left (FP1, AF3); Prefrontal-right (FP2, AF4); Frontal-left (F1, F3, F5, F7, FC1, FC3, FC5); Frontal-right (F2, F4, F6, F8, FC2, FC4, FC6); Frontal-midline (FPZ, FZ, FCZ); Central-midline (CZ, CPZ); Parieto-occipital-midline (PZ, POZ, OZ); Central-left (C1, C3, C5); Central-right (C2, C4, C6); Parietal-left (CP1, CP3, CP5, P1, P3, P5, P7); Parietal-right (CP2, CP4, CP6, P2, P4, P6, P8); Occipital-left (PO3, PO5, PO7, O1); Occipital-right (PO4, PO6, PO8, O2). Further analyses were performed using the mean spectral power in each functional set.

From this point on, two experimental approaches were used in parallel, taking into account the set of samples evaluated; the subject-dependent approach in which each individual was evaluated separately and a subject-independent in which the data of all subjects were taken into account at the same time.

In order to evaluate the best trial time, an initial classification was carried out using various linear and non-linear classifiers. For the linear feature extraction method, linear discriminant analysis (LDA), quadratic discriminant analysis (QDA) and non-linear kernel Support Vector Machine (SVM) classifiers were tested. In the non-linear condition of feature extraction, the list of evaluated classifiers was augmented to 8 classifiers: LDA, QDA, linear-SVM, non-linear-SVM, k-nearest neighbors (KNN), Gaussian Naive Bayes (GNB), Gradient Boosting (GB) and Random Forest (RF).

3.2.2. Feature Selection

Once the optimal window size has been specified, we moved on to the selection of frequency-location sets containing the emotional information. Beginning with the features extracted according to the traditional Fourier method, two classifications were made, SD and SI, by means of a SVM classifier for each set of frequency (6 bands) – location (13 regions), obtaining the classification performance for each one of the 78 variables studied. The frequency-location pairs that obtained the best results were selected to elaborate the final computational model capable of recognizing positive and negative emotions. On the other hand, the selection of the features extracted by the wavelets method was performed using the recursive feature elimination (RFE) technique for the SD approximation and the simulated annealing (SA) technique for the SI approximation. As a result, from each approach a proposal of computational model was obtained for the recognition of emotions in the valence scale.

3.2.3. Classification

The three obtained computational model proposals, based on the specified time window and the frequency-location features extracted in each method, were evaluated in a final classification stage. The classification was made for both SD and SI approximations; with the classifiers that showed the best results in the previous steps of feature extraction and selection.

3.2.4. Cerebral Asymmetries

In order to further explore the neural substrates involved in the processing of positive and negative emotions, a study of interhemispheric asymmetries was performed. Two methods were used, the classical method based on the differences of the spectral power of homologous interhemispheric regions, and a more modern method based on the differential entropy of the spectral signal also in homologous cortical regions. For this, the signal of each of the 13 functional sets, in the 6 frequency bands of studied, using the optimum trial time obtained in the previous analyses and the feature extraction method that gave the best results was used.

3.3. ECG

The ECG signal was recorded by two electrodes positioned in lead II, using the same NeuroScan system (Compumedics, Charlotte, NC, USA) used for the recording of the EEG activity. The signal of 5 subjects from the total of 24 subjects participating in the study was not correctly recorded so they had to be excluded from the ECG study. The different HRV measurements for each subject and each video were obtained thanks to the software Artiifact 2.09 [219]. In total, 19 HRV variables were calculated, 7 features in the time domain, 9 in the frequency domain and 3 from the Pointcaré plot. The Mann-Whitney statistical test was used to check the differences between the positive and negative emotional categories for each variable in the total sample and separately between men and women. In addition, the simulated annealing method was used to select those features relevant for the recognition of emotions in the valence scale.

3.4. Skin Temperature

The skin temperature was obtained using the ActTrust bracelet (Condor Instruments Ltda., Brazil), positioned on the right wrist of the participants. Also due to problems during signal recording, 2 of the participants had to be excluded from the study. As with ECG data, differences between emotional categories were statistically verified by the Mann-Whitney test, for the total sample and by gender.

3.5. Multimodal Approximation

After specifying the time window, the relevant frequency-location sets, the EEG feature extraction method and the optimal physiological features for the classification of positive and negative emotions, we performed a final classification taking into account the three biological signals studied. Due to lack of physiological data on some subjects, this step was performed with only 18 of the 24 subjects participating in the study. Classification was carried out using KNN and QDA classifiers taking into account 22 variables, 20 from the EEG, 1 from the HRV measures and the skin temperature. Three classifications were made, one contemplating the total sample, and two others taking gender into account.

4. Results

As in the methods section, in this part we summarize the most relevant results of this doctoral thesis, without going into details, as these can be found in the presented papers.

The main objective of this doctoral thesis is the study of positive and negative emotions at the cortical and ANS levels, with the purpose of specifying the necessary parameters for the real-time recognition of emotions on the valence scale. In order to achieve this, the correct emotional stimulation of the subjects is key, so we asked the participants to value their emotional experience after each video clip. The scores given coincided on the valence scale with the positive and negative content of the videos in our own-design audiovisual database. The average rating for positive videos was 7.51 (std 1.6), and for negative videos 2.91 (std 0.98). However, the differences were not as clear, at the level of the general sample, in the arousal scale, the videos categorized as positive and negative obtained values of 3.76 (std 1.62) and 5.47 (std 1.35), respectively.

As we have seen throughout the development of this thesis, in order to achieve a real time emotion recognition system based on the EEG it is necessary to fix a series of parameters such as the feature extraction method on the frequency domain, the size of the trial window, the relevant frequency-location features that contain the emotional information and the optimal classifier in order to recognize the categories of study.

Looking at the time window that masks the emotional process, we have seen that in all conditions (SD and SI approaches; linear and non-linear feature extraction methods; and the different classifiers used) the same tendency occurs of increasing the accuracy of the classification as the size of the trial window was raised; that is, there was a positive correlation between the time window and the performance of the classification of positive and negative emotions. The maximum success achieved, in both linear and non-linear feature extraction conditions, took place in the 12-second window. However, it is worth mentioning that, although in the SD approximation 100% of average success was achieved among the subjects in the 12-second window; for the SI approximation these results were not that good, although they did maintain the correlation mentioned. In studying the window time, the performance of different classifiers in recognizing positive and negative emotions was also compared. In the case of the feature extraction with linear methods, 3 classifiers were compared, of which the QDA obtained the best results. In the case of the extraction of frequency features by means of wavelets, of the total of classifiers tested, there were several that presented the best result, without showing significant differences between them, the classifiers were QDA, l-SVM, nonl-SVM, RF and KNN. However, the lowest variability showed corresponded to QDA and KNN classifiers, so they were chosen for the following analyses. The percentages of accuracy obtained by the best classifiers in the 12-second window in SD mode were 100% (std 0) for QDA-Fourier, 99.69% (std 0.48) for QDA-Wavelets and 99.75% (std 0.78) for KNN-Wavelets.

Taking into account the trial time window specified in the previous step, feature selection for each frequency extraction method was made. From the lineal method, 25 features were selected coming from the SI sample attending to the subjective-rating (SR) criterion of the stimuli, which had shown better results than the population-rating criterion (PR). On the other hand, the combination of features that best results presented, with the non-lineal method for feature extraction, were 20 features coming from the SD-PR approximation. The most relevant frequency-location pairs in positive and negative emotion classification resulting from the two feature extraction methods, are shown in *Table 2*.

Table 2. Most relevant frequency-location features selected from both linear and non-linear feature extraction methods. Grey dotted lines indicate those coincident regions between methods.

Frequency band	Lineal Feature Extraction	Non-lineal Feature Extraction
Delta		
Theta		
Alpha	PreFrontal left PreFrontal right Frontal midline Frontal left Frontal right Central right Central midline Parietal left Parietal right Parieto-occipital midline Occipital left Occipital right	PreFrontal left PreFrontal right Central midline
Beta1	PreFrontal left PreFrontal right Frontal right Central midline	PreFrontal left PreFrontal right Frontal midline Central midline Parieto-occipital midline Occipital right
Beta2	PreFrontal left PreFrontal right Frontal midline Frontal left	PreFrontal left PreFrontal right Parieto-occipital midline Occipital right
Gamma	PreFrontal left PreFrontal right Frontal midline Frontal left Central left	PreFrontal left PreFrontal right Frontal midline Central left Central right Parietal right Occipital right

Applying the resulting computational model in each feature extraction method, the classification results for the lineal method with the non-linear SVM classifier were 94.64% (s.d. 4.33) SD-PR, 55.43% SI-PR, 94.64% (s.d. 5.37) SD-SR and 60.08% SI-SR. Regarding the non-lineal feature extraction model, results were expressed attending to the F1-score instead of the accuracy; the QDA classifier obtained 0.98 (±0.014) for the SD-PR condition and 0.524 (± 0.082) for the SI-PR; 0.989 (±0.013) SD-PR and 0.522 (± 0.092) SI-PR were the results obtained by the KNN classifier. Although in the case of linear extraction methods, classification differences were observed between the stimulus labelling criteria (subjective or objective), in the non-linear approach no such differences between criteria were observed.

Once the computational model based on the EEG signal has been established, having set the optimal parameters for the recognition of positive and negative emotions such as the method of feature extraction, the time window in which emotion is encoded, the informative frequency-location pairs, the stimulus labeling criteria and the optimal classifier for our signal; we studied the emotional response that took place at the level of the ANS, in two of its effectors, the HRV which represents the cardiac function and the skin temperature. No significant common differences between emotional categories were found in any of the HRV measures. However, two variables showed differences in the response to positive and negative emotions when separating the sample by gender, being the significant variable for men the one denominated as NN50 corresponding to the time domain variables, and the SD2 measure resulting from the Pointcaré plot in women. In the case of skin temperature, this measure was statistically different between the emotional conditions studied, both at the individual level (SD) and at the total sample level (SI). However, evaluating gender differences, this result was not observed in men, but in women.

Taking into account the computational model obtained from the EEG and the variables that showed significant differences at the physiological level, a multimodal classification was performed to evaluate the contribution of the peripheral and central nervous systems. Classification was carried out in both SD and SI modalities with QDA and KNN classifiers. In SD mode, no significant differences were observed in combining EEG variables with skin temperature and HRV resultant variables. However, despite the differences between the conditions described, the classification taking into account only the ANS variables showed worse results. In the SI approximation, no differences were observed between the different combinations, moreover, all of them continued to show classification results around chance, so it was not possible to draw conclusions from this study regarding the contribution of the different branches of the nervous system.

Finally, to study in more detail the neural sources involved in the processing of emotional information on the valence scale, we conducted a study of interhemispheric asymmetries taking into account each frequency band studied. The different used methods showed similar results, remarking that (1) there was interhemispheric lateralization at all levels of the cortex, from the prefrontal level to the occipital level. (2) In general, positive and negative emotions lateralized towards opposite hemispheres following a left-positive and right-negative pattern at frontal level, and opposite, right-positive and left-negative pattern at parieto-occipital level. (3) This lateralization pattern was different for the low and high frequencies of the EEG spectrum, showing opposite activity to each other. (4) In general, the right hemisphere appeared to have more activity than the left at both emotional categories. (5) Greater activity was also observed in rostral cortical zones compared to caudal regions, i.e., the prefrontal cortex showed greater activity during the processing of emotions on the valence scale.

5. Discussion

As we have seen throughout the development of this doctoral thesis, elaborating a system capable of recognizing emotions is a complicated task that depends on numerous factors, such as the emotional theoretical model followed or the components of the emotional episode taken into account, and these in turn depend on numerous variables. Thus, the number of computational models resulting from the possible combinations of the multiple factors, explains the variability that currently exists between the works and authors focused on the study of emotions.

Starting from the main bias in the study of emotions, which is the choice of the theoretical model, we have focused on the dimensional model of emotions, specifically in the emotional valence. Our audiovisual database used for emotional stimulation has been polarized in the valence scale but not in the arousal scale, in the population sample studied. Hence, we were able to associate the changes in the cerebral and corporal responses to the effect of this dimension.

5.1. EEG-Based Emotion Recognition

The main objective of this doctoral thesis has been to try to establish a series of parameters necessary to the development of a computational model capable of recognizing positive and negative emotions, focused on real-time and based on the EEG. To give rise to our computational model, a total of five factors have been specified, which we will briefly discuss below, since they are reasoned in detail in the corresponding articles.

Although the primary objective of computational affective neuroscience is to generate a model of emotion recognition based on the common or universal characteristics of the emotional neural process, in order to reduce the economic and temporal cost and the complexity of the aBCI applications; the subject-independent approximation is complicated due to the high number of factors, still to be controlled, that contribute to inter-subject variability, making the resolution of the algorithm very complicated. In this way, although we have tried to search for this universal algorithm, the main findings are based on the subject-dependent approach, which, although had allowed us to elaborate a common model, it is not based on the desired subject-independent strategy.

Traditionally, the EEG spectral analysis was based on Fourier transform [220]. The technique assumes that the EEG signal is formed by the conglomeration of different sinusoidal waves characterized by a specific frequency with constant phases and amplitudes and being a stationary process, i.e. mean and variance do not change over time. However, we are talking about the brain as a large-scale level of individual neuron activity, interconnected at networks that are widely distributed, where the EEG signal is the summation of millions of neural networks; at this large scale patterns of neuronal activity, linearity is not achieved. Therefore, although the EEG signal has been treated with stationary and linear methods, its nature is nonstationary and nonlinear [221].

Aiming to design an efficient real-time emotion recognition system based on EEG, we have to care about the efficient resolution of the technique to extract the power spectral density of the signal at the different bandwidths of interest, without forgetting the speed of the process. Although, the fast Fourier transform leads the race in terms of speed, Wavelet transform is more faithful with the non-stationary nature of the EEG signal and has less time cost in comparison with other non-linear algorithms [222]. For these reasons and based on our classification results, the non-linear feature extraction method based on the wavelet packets decomposition method was selected to form part of our emotional model.

Second, the size of the trial window necessary for the recognition of emotions on the valence scale was set at 12 seconds because this time window was the one with the highest percentage of success and the lowest standard deviation in the classification. Although it is interesting to consider the fact that from the 8-second window it seems that a plateau was established, because although the classification and standard deviation improved as the window increased, they did not do so significantly. This result suggests that emotional information is encoded at an interval of about 8-12 seconds. However, in order to verify this fact, it would be necessary to continue increasing the size of the window to see if the plateau is maintained or at some point the performance of the classification begins to worsen, thus delimiting the temporal factor of the emotional cognitive component.

Third, as it is expected that the emotional information is processed by specific neural pathways, the features of the EEG that reflect this process must be located in specific components of the space and frequency domains. 20 variables based on the spectral frequency of the EEG and cortical location have been selected as the most relevant for the coding of the emotional information and therefore to form part of our computational model. In terms of location, the most noteworthy components were the prefrontal region, central region, the midline and the right occipital region. The resulting zones corresponded to five of the six functional groups defined by Kober et al. ([96]), presented in section 1.2., the Lateral Occipital/Visual Association group, Medial Posterior group, Cognitive/Motor group, Lateral Paralimbic group and Medial PreFrontal cortex group. As for the most relevant frequencies, our studies decoupled the low frequencies (delta and theta) with the processing of positive and negative emotions; and showed the gamma frequency of 31-44Hz as one of the most relevant, distributed over most of the highlighted regions. Once the relevant regions in the processing of emotions on the valence scale have been established, we studied in greater detail the relationship on their frequencies. Our results showed that during the processing of positive and negative emotions, the brain activity lateralized towards opposite hemispheres in homologous regions, coinciding with the pattern of prefrontal asymmetry described by Davidson et al. [52]. In addition, our asymmetry studies coincided with the relevant frequency-location pairs in that the right hemisphere generally presents more activity than the left, suggesting a possible specialization of the right hemisphere in the processing of emotions [223], [224]. However, in order to make a more detailed interpretation or hypothesis about the functioning of the possible emotional valence processing pathway, it would be necessary to continue with the analyses and delve into the frequency relationships between regions. For the moment, we can conclude that the selection of the 20 frequency-location features that make up our computational model, allows us a precise subject-dependent classification of positive and negative emotions, in addition to needing fewer electrodes, and therefore, reducing the preparation time of participants and the complexity of the setup.

Fourth, the classifiers that have been shown to be most effective and suitable for the classification of positive and negative emotions based on the EEG signal were the non-linear classifiers QDA and KNN. Finally, we have seen that the subjective criterion for labeling the emotional stimuli was not relevant for the classification of positive and negative emotions, that is, it was not necessary to attend to the individually subjective emotional scores of the participants. We have obtained the same results when using either the population label criterion or the subjective label criterion. Therefore, in order to gain time in future applications, subjective ratings could be omitted. However, this fact may be influencing the subject-independent classification as represents one more source of inter-subject variability. In addition, it may be giving us a clue about the conscious and unconscious cognitive emotional components. Consequently, future work assessing in more detail the implication of the subjective scores in the emotional process could be interesting.

Lastly, it is worth to mention that in order to recognize emotions in real-time, it is also necessary to specify and implement the methods of signal pre-processing and elimination of artifacts. The applied methods must take into account the time cost that may introduce in the process, therefore they must be efficient in terms of data cleaning and time consuming. Although, our final goal was to create an aBCI system capable of recognizing emotions in real-time, the present project was conducted offline to specify the features and parameters needed for the real-time implementation, for this reason, we did not delve into real-time signal pre-processing methods.

5.2. The Physiological Aspect of Emotion

The authors who support the dimensional theory of emotions have attempted to relate the emotional somatic component, i.e. the state of the ANS, with the motivational systems of approximation and withdrawal, which in theory would be engaged during the processing of positive and negative emotions, respectively. Specifically, the activation of PNS would take place when approximation responses generated by positive emotional stimuli were given, and, on the contrary, SNS would be actively involved in rejection responses in front of negative stimuli. However, the results found in the present thesis, although they showed different patterns of response to positive and negative stimuli, these did not coincide with the expected response generated by the parasympathetic and sympathetic systems in the emotional conditions studied; or at least, the relationship expected between the motivational systems and the divisions of the ANS has not been supported by our results. At cardiac level, the variables, NN50 and SD2, in which significant differences have been found in the responses to both emotional conditions, although only when separating the sample by gender, are regulated by both divisions of the ANS. The fact that both variables are regulated by both systems suggests that there is an activation of the ANS in general when both positive and negative emotional episodes take place. This activation mediated by the dimension of the emotional valence, at the cardiac level seems to prepare men for an immediate response more evident in positive emotions, as HRV increases in the short-term; and women for a longer-term adaptability to negative emotions. In general, we could say that positive emotions unleash greater activities in the short-term and that negative emotions trigger larger long-term variations in cardiac activity. On the other hand, in the case of the skin effectors, which are only regulated by the SNS, the expected response following the hypothesis of the relationship between the motivational systems and the somatic responses, would be vasoconstriction and therefore the lowering of the temperature when negative emotions, and vasodilatation - increase of the temperature during the processing of positive emotions. However, this response has not been the one found, but rather there has been an increase in temperature, suggesting vasodilatation, in both conditions, being greater for negative emotions. These results indicate an increase in SNS activity at both emotional conditions, although the form in which it occurs does not coincide with the expected theoretical response. For all these reasons, we can conclude that the dimension of emotional valence does mediate different responses at the level of the ANS, but that more detailed studies are necessary in order to make inferences about its physiology.

With respect to the temporality of emotion, in this doctoral thesis we have gone much deeper into the cognitive component than the somatic one. The ideal is to extract HRV measurements from long fragments of time of about 5 minutes, however, our stimuli were of short duration and if we had also fragmented them, like the EEG signal, to be able to study the time of emotion, the results might not be representative [151]. As far as HRV is concerned, we simply wanted to check its state against the processing of positive and negative emotions by means of traditional HRV methodology, but without the objective of drawing conclusions for real time applications. As standard methods of HRV require long-time recordings, new algorithms have been developed in order to detect HRV instantaneous changes, based on beat-to-beat dynamics, to face real-time applications (e.g. [225], [226]). In the case of skin temperature, we did not study its temporality either, but we evaluated the response in the total set of each video. The classification obtained with the whole physiological data did not showed neither improvements nor worsen in performance when used in combination with the EEG data. However, when carrying out classification separately, physiological signals obtained worse classification results than cerebral signals. In order to have a more detailed view of the somatic emotional component, not only with theoretical purposes but also with practical ones, the study of the ANS instantaneous changes in the response to emotional stimuli would be very interesting.

5.3. Gender Differences in Emotion

As Hagemann et al. [148] presented different responses of the central and the autonomic nervous systems depending on gender, it would not be nonsensical to think that these differences may also be present at the emotional level. Our preliminary results in terms of gender, showed that there are different response patterns at the peripheral level, both in the cardiac and cutaneous responses. This could suggest that men and women have developed different patterns of body response to positive and negative emotions. In general, our results suggested that women respond more reactively to negative stimuli than men, at the ANS level. However, at the CNS level, although the relationship of frequencies between genders has not been studied; when separating the sample by gender, men and women did not obtain different classification results; suggesting that there are no gender differences in the neural pathways that process the emotional information. The hypothesis that at the central level the neural pathways and their functionality are not different between genders, but the responses at the peripheral level are, suggests a wide range of adaptive responses in our behavior beyond the primitive "fight or fligh" or "relax-eat".

5.4. Final Thoughts and Future Perspectives

In this doctoral thesis I present a computational model for the classification of positive and negative emotions based on the EEG signal, which has shown not inconsiderable results in the subject-dependent classification. However, it has not been possible to elaborate a model taking into account the subject-independent approach, thus highlighting the well-known problem of high inter-subject variability concerning the study of the EEG signal. The novelty of this work is that, although we started from a subject-dependent approach, we have elaborated a subject-independent model that allowed us to reduce the dimensionality of the process, without punishing classification performance, in order to reduce the preparation and training time for real applications by skipping the step of feature selection for each subject individually and diminishing the number of electrodes required. Applying our computational model, in which the trial window size in which to extract the frequency features of the EEG signal is fixed and the specific frequencies to be extracted from each particular channel; the classifier was able to differentiate positive and negative emotions with a precision close to 100% accuracy when using training data of the same subject. However, if the classifier was trained with the data of different subjects, it was not able to classify the positive and negative emotions of a new subject. Although there is theoretical evidence that contributes to the idea that inter-subject variability is mainly due to the intrinsic cerebral variability inherent in the functioning of a healthy brain, the fact that the subject-independent classification fails in comparison with the subject-dependent classification, using the same features, is disconcerting.

Like all affective computing works that try to classify and recognize emotions, we have had to assume an emotional theory, which, like all of them, may or may not be correct, this fact makes it possible to question the results of the present thesis as to whether or not the appropriate primary emotional component has been measured. One of the main drawbacks of the dimensional theory is that two types of emotions differentiated in the discrete model, such as fear and anger, would be found within the same dimensional space, negative valence and high arousal, even though the subjective feeling is clearly different. At this point it is worth asking whether the classification and recognition of emotions should take into account the combination of both models and, therefore, use a different approach to those used to date. Some authors have already proposed combined models, as the Geneva Emotion Wheel [83]; however, the assumption that discrete emotions have their own region, overlapping or not, in the bi-dimensional valence-arousal space, should also imply psychological and physiological changes according to. Therefore, it would be interesting to study our data from the point of view of the theory of discrete emotions. However, on a more theoretical level, the reason why we can differentiate discrete emotions is subjective, that is, when we realize that we are experiencing an emotion is because the conscious cognitive component has taken place. This fact leads us to the debate on the definition of the basic components of emotion and their temporal order, previously dealt with in section XX. It seems logical that there is an unconscious evaluation of the stimulus that recruits the appropriate motivational system, triggers a response at the physiological level (ANS and facial and body expressions) and provokes the feeling at the cognitive-conscious level. But is there an order of recruitment of the emotional components or are they all activated at the same time? If emotion is the assortment of all processes, it is clear that with physiological signals we are measuring the somatic component; but what do we measure with neuroimaging techniques? According to this theory, the four emotional components (unconscious cognitive, somatic, motivational and conscious cognitive) are based on different neural networks or structures; for example, the somatic component will be regulated by more primitive brain regions such as the brainstem. So, what process do brain signal recordings represent? In principle, all of them, however, we are limiting our search by adopting an emotional model, and depending on the spatial resolution and characteristics of the neuroimaging technique used. Furthermore, despite the attempts of computer models such as Scherer's GENESE expert system [227], which tries to evaluate stimuli objectively based on specific characteristics of their content; for the time being, the emotional experience can only be measured through the subjective expression of the participants, the conscious cognitive component. This fact generates even more unknowns given that stimuli scores are subject to being modified,

since, as discussed in more detail in the second of the articles that make up the present doctoral thesis, the evaluation of an emotional episode can be consciously altered by valuing previous experiences and cultural concepts, not being faithful to the pure lived emotional experience. Despite the advances that are taking place at a practical level in the area of the study of emotions, there are still many unknowns to be deciphered regarding the neurobiology of emotional processes.

As future perspectives following the line of this work, it would be interesting (1) to continue evaluating the sizes of the trial window, to see if the plateau found between 8 and 12 seconds is maintained or begins to decrease at some point; (2) to carry out a study of coherence and phases to have a better vision of the relations between the cortical areas involved in the processing of positive and negative emotions; (3) to apply our computational model in other publicly available emotional databases, to evaluate its effectiveness in other populations and facing different audiovisual stimuli also labeled in the valence dimension; (4) to evaluate the effectiveness of the model in a real-time application; (5) to enlarge the study sample in order to study in more detail gender differences and differences in the labeling stimuli criteria.

6. Conclusions / Conclusiones

Conclusions

1. Electroencephalography techniques are useful for analyzing the cerebral processing of emotions.
2. The electroencephalography technique allows the classification of positive and negative emotions with a success rate close to 100%, in a subject-dependent approximation, by means of a set of 20 frequency-location features.
3. The information on emotional valence, encoded in the electroencephalographic signal, is framed in time windows of 8 to 12 seconds in duration and includes from the alpha band to the gamma band in the spectrum of the electroencephalographic signal.
4. The cortical regions involved in processing the information relative to the emotional valence dimension appear to be located along the prefrontal, central, parieto-occipital areas and along the entire midline.
5. The prefrontal cortex and the right hemisphere show more activity than other cortical regions during the processing of positive and negative emotions.
6. During the processing of positive and negative emotions, there are cortical asymmetries in the electroencephalography signal, so that in the rostral regions there is a lateralization towards the left hemisphere during the experience of positive emotions and towards the right hemisphere in the negative ones. In the more caudal regions, the opposite occurs.
7. Non-linear methods of feature extraction show better results than traditional linear methods in the classification of bivalent primary emotions based on electroencephalography.
8. The non-linear classifiers, QDA and KNN, present the best performance for the recognition of positive and negative emotions using electroencephalography techniques.
9. Positive and negative emotions are accompanied by effects at the level of the autonomic nervous system, including changes in heart rate variability and skin temperature.
10. Brain bioelectrical activity achieves better classification performance of bivalent primary emotions than signals from the autonomic nervous system. The combination of both types of signals does not significantly improve the classification results.

Conclusiones

1. Las técnicas de electroencefalografía son útiles para analizar el procesamiento cerebral de las emociones.
2. La técnica de electroencefalografía permite clasificar emociones positivas y negativas con un porcentaje de acierto cercano al 100%, en una aproximación sujeto-dependiente, mediante un conjunto de 20 características de frecuencia-localización.
3. La información relativa a la valencia emocional, codificada en la señal de electroencefalografía, se enmarca en ventanas de tiempo de 8 a 12 segundos de duración e incluye desde la banda alfa hasta la banda gamma en el espectro de la señal de electroencefalografía.
4. Las regiones corticales implicadas en el procesamiento de la información de la dimensión de la valencia emocional parecen estar localizadas a lo largo de las áreas prefrontales, centrales, parieto-occipitales y a lo largo de toda la línea media.
5. La corteza prefrontal y el hemisferio derecho muestran mayor actividad que otras regiones corticales durante el procesamiento de emociones positivas y negativas.
6. Durante el procesamiento de emociones positivas y negativas, existen asimetrías corticales en la señal de electroencefalografía, de manera que en las regiones rostrales existe una lateralización hacia el hemisferio izquierdo durante la experimentación de emociones positivas y hacia el hemisferio derecho en las negativas. En las regiones más caudales se produce lo contrario.
7. Los métodos no-lineales de extracción de características muestran mejores resultados que los métodos lineales tradicionales, en la clasificación de emociones primarias bivalentes basada en electroencefalografía.
8. Los clasificadores no-lineales, QDA y KNN, son los que presentan un mejor rendimiento para el reconocimiento de emociones positivas y negativas utilizando técnicas de electroencefalografía.
9. Las emociones positivas y negativas se acompañan de efectos a nivel del sistema nervioso autónomo, que incluyen cambios en la variabilidad cardiaca y en la temperatura de la piel.
10. La actividad bioelectrica cerebral logra un mejor rendimiento de clasificación de emociones primarias bivalentes, que las señales procedentes del sistema nervioso autónomo. La combinación de ambos tipos de señales no mejora de manera significativa los resultados de la clasificación.

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