Psychophysiological Methods in Language Research

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Rethinking Embodiment in Studies of Linguistic Behaviors

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BAHIYYIH HARDACRE

FOREWORD BY JOHN SCHUMANN

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For Jairo, Judy, and Todd

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Foreword

I am very pleased to introduce the author of this book, Dr. Bahiyyih Hardacre. She received her doctoral degree in Applied Linguistics from UCLA in 2015. As a doctoral student, she pursued studies in language acquisition and use. She became very interested in the biological basis for language and studied neuroanatomy with Dr. Arnold Scheibel and neurophysiology with Dr. David Shapiro. Her doctoral dissertation *Biological and Psychophysiological Correlates of Conversation* examined physiological manifestations of turn-taking among speakers of English as a second language. During that time, she became knowledgeable and proficient in the use of several psychophysiological technologies. Additionally, she received training from the Center for Culture, Brain and Development at UCLA, and now is a professor in Applied and Advanced Studies in Education, a division in the Charter College of Education at California State University Los Angeles.

The term “mind” appears to be an abstract, nonphysical concept. You can’t really point to it, or see it, or hear it, or touch it. But today the concept “mind” is understood by many to refer to the brain, the body proper, the physical environment and the cultural environment, and our activity in the environment. This formulation is often described as the 4Es. Thus, the mind is embrained, embodied, embedded, and enactive. A great deal of research in applied linguistics and second-language acquisition has been examining the linguistic input to and output from second-language learners, but this input and output is processed by the mind. So, there has been a strong desire on the part of researchers to be able to know how the mind processes the language that learners are exposed to and the language that the learner produces. Researchers so far have been looking at external phenomena, and the question has been, “How can we look at the internal phenomena as they are processed by the brain and the body?” This book is about how to do that. Over the years, and especially recently, technology has been developed that allows research to be done on what happens in the brain and in the body during the acquisition and use of language. Thus, we now have some ways to observe the inside.

THE BRAIN

It is possible to have a direct measure of brain activity while it tackles language-related tasks. Brain waves during language use can be measured via event-related potentials (ERPs) with electroencephalography. In addition, with various forms of functional resonance imaging (fMRI), actual neural activity related to language processing can be observed.

THE BODY

The body also has the potential of providing enlightening information about language learners' and users' abilities, behaviors, attitudes, and motivations. Through the measurement of physiological responses while engaged with language-related tasks, researchers can explore how the mind intertwines with the body's autonomic system. Therefore, the body's physiological recording methods that have been included in this book (i.e., electrocardiography, blood pressure, electrodermal activity, skin temperature, eye movement and eye tracking, respiration, and facial expression analysis) are potential mechanisms to explore the feedback from the body and the effect on the body that are linked to language learning and use.

Fortunately, the measurement of physiological responses can be easily achieved due to a growing number of high precision and reliable technological devices and data processing technology. For example, wearable technology allows the long-term, online, and simultaneous recording of heart rate, blood pressure, electrodermal activity and skin temperature; eye trackers and EEG caps have become less expensive and widely available; facial expression analysis and the extrapolation of heart rate variability have become more accessible with the emergence of very affordable data processing software.

Thus, we are no longer faced with a Black Box with respect to internal processing during language acquisition and use. However, as Dr. Hardacre makes clear, while the box is no longer black, it is still cloudy, but at least we can get a view from the inside.

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Introduction

Over the last few decades, scientific endeavors within the scope of humanities have gradually moved away from *intradisciplinarity*, that is, working within a single discipline, and toward *multidisciplinary*, that is, merging multiple branches of knowledge. This trend has led to successful collaborations among teams of researchers from different disciplines. Funding agencies, academic journals, and professional conferences often invite contributors to work collaboratively and to think *crossdisciplinarily*, to view their disciplines from the perspective of another, and *transdisciplinarily*, to push their research goals beyond their disciplinary borders by integrating methods and perspectives from other branches of knowledge. One area of research that has fully embraced transdisciplinarity is language research.

The rapid expansion of transdisciplinarity in language research can be attributed to the fact that it provides an opportunity for greater scientific exploration. It allows language studies to be carried out in a larger scale. It offers the means to acquire authentic, relevant, and hard data. Transdisciplinarity has contributed to the creation of several disciplinary branches, such as neurolinguistics, ethnolinguistics, sociolinguistics, computational linguistics, corpus linguistics, and applied linguistics, to name a few. This expansion was largely due to the fact that the improvement of technology has made access to certain kinds of data more convenient.

One example of transdisciplinarity in language research is the use of corpus-based computational linguistics in statistical natural language processing research. The analysis of large corpora of authentic spoken (transcribed) and written language from different genres through the employment of search toolkits and computer algorithms has helped researchers of natural language processing make significant progress in the development of machine learning and machine translation models.

Transdisciplinarity has become the very heart of applied linguistics, a field that aims at developing understandings of and solutions to language-related problems through bridging language research to the fields of education, communication, anthropology, sociology, psychology, and psychophysiology. Most research studies in applied linguistics make use of various kinds of documentation of language users' competence and performance, such as language tests, surveys, samples of writing, transcripts of oral production, corpora, focus groups, interviews, or think aloud protocols. Additionally, studies about conversational and linguistic behaviors may video- or audio-record study participants' use of language at various settings, such as at a doctor's office, in a classroom, in a courtroom, during a family gathering, or in front of a large audience, for example. These recordings help the researcher study certain aspects of the language performance after the fact, which requires replaying the audio file multiple times in order to transcribe it, to analyze pitch and intonation contours, to assess the phonetic quality of segmental and suprasegmental phonological features, to measure the length of pauses and silences within and between words and sentences, to count the number of occurrences of certain linguistic patterns, among other purposes. The addition of video data also allows the researcher to code it for facial expressions, gaze orientation, body language, and gestures, which can be later quantified and correlated with the discourse content, prosodic features, and interactional practices occurring during the examined linguistic performance.

The pairing of transcribed text with coded gaze, facial expressions, gestures, pitch, intonation, context, setting, the placement of other participants and objects in the environment is the foundation of discourse analysis. Discourse analysis has had an important role in expanding research in applied linguistics. Because language is an integral part of all social phenomena, it needs to be examined through a standardized system that allows for the inclusion of other variables, such as pragmatics, rhetoric, ethnographic context, among others. By adding several layers of analysis to the study of language, researchers need to account for multiple factors that frame the social activity (Geenen, Norris, & Makboon, 2015; Norris, 2013). Simply analyzing the language (in oral, signed, or written form) used in a particular situation results in a fundamentally incomplete picture of what is happening during the ongoing interaction. While language does represent in part the examined communicative event, it is certainly not the only significant mode; there are additional sources of nonverbal information at the disposal of an interactional co-participant that may not involve the use of language at all. Current research has shown that multimodal representation of language use, paired with individual characteristics and behavior, during communicative events is not only desirable but achievable, especially with the rise of increasingly affordable biometric technology. Non-intrusive and more accessible physiological recorders have drawn attention of multimodal discourse analysts as they afford the monitoring of emotional regulatory responses during the social engagements under research scrutiny.

By relying on the describable action within an interactional framework, research on embodiment has been able to make assumptions about the co-participants' relationships in terms of epistemic status, stance, underlying meanings, intentions, and agendas during a given interaction. Even though participants do not have direct access to other participants' abstract thoughts, much of the content from such thoughts and intentions find their way out of interactants' brains into the immediately accessible medium. This is because eye movements, feet fidgeting, and head, hand, arm, and leg positioning can express a participant's stance and attitude toward the content of the talk, either when they are producing the talk themselves, or when they are its recipient. It is through these bodily displays that co-participants display their stance, positionality, and intentionality.

One important area of language research that lends itself to psychophysiological methods is the study of intentionality. Intentionality is the intrinsic mental phenomenon (Searle, 1983) that precedes speech acts or communicative behaviors. Effective communication requires that the hearer captures the meaning intended by the speaker provided that it was the speaker's intention to be understood. Paul Grice (1957) defined the expression of meaning as attempts to communicate involving intentions that a speaker has to produce effects on hearers. John Searle's (1989) description of meaning was different from Grice's in that in his perspective, meaning depends on individual intentionality and social norms. Searle argued that we need to distinguish between the intention to represent certain state of affairs in certain illocutionary modes from the intention to communicate those representations to a hearer. According to him, the study of language was part of the study of human behavior, leading to the idea that speech acts are like other acts by involving intentional production of consequences. Both Grice and Searle agree on the fact that what makes speech acts different from other kinds of behavior is that they carry intrinsic meaning, but for them to have meaning, they must be intended as signals in a certain way that is understood by the hearer.

At the very core of the concept of meaning is a communication co-participant that can understand the uttered words and sentences, based on a set of previously established rules and parameters. Searle (1989) argues that communication involves producing certain sounds with one's mouth or markings on a paper, just like any other human behavior, but these signs have pre-established semantic properties. They acquire representational properties understood by other language users because the hearer's mind is able to assign intentionality on these sounds and marks; in fact, our mind is able to impose intentionality even on entities that are not intrinsically intentional to start with.

Besides analyzing meaning and speech acts in terms of individual intentionality, Searle also described meaning as a social phenomenon. From the social phenomenon perspective, meaning cannot be assigned unilaterally by the speaker on otherwise neutral sounds and marks. For random signs that are produced by a speaker to have meaning to a hearer, they have to have been agreed upon beforehand. The creation of speaker's meaning essentially requires human practices, rules, and conventions that have been developed after a number of meaning-making communicative interactions and negotiations.

Searle (2002) argues that intentional mental phenomena are part of the natural maintenance of our biological life, which includes the expressions of thirst, hunger, emotions, breathing, digestion, and so on. For example, the neurobiological processes that trigger the sensation of thirst will lead an individual to search for and drink water. Intrinsic intentional phenomena of this sort are caused by neurophysiological processes governed by the autonomic nervous systems of these organisms.

According to Searle (2002), it is a biological fact that certain mental states function causally in the interactions between the organism and the production of the behavior of the individual. In that sense, it is just a fact of biology that thirst will cause an organism to drink water. In the case of human social behavior, at a much more sophisticated though equally neurobiological level, the belief system a person has about what is in their best interest may play a causal role in their behavior in general, such as choosing a suitable and safe place to live, healthy foods to eat, a desirable occupation, and even to whom to socially interact and which languages to learn. Therefore, it is clear that the study of intentionality must take into account the psychological and physiological underpinnings of emotional states and autonomic responses.

The description of human behavior as the expression of intentionality during a dyadic or group communicative event requires mutual understanding so that it is successfully interpreted by its co-participants. Intentionality elevates the body to a biosemiotic resource of shared referential knowledge. This shared referential knowledge includes the mutual understanding of how gestures, facial expressions, movements, enactments, and physical orientation of co-participants to each other or to objects in the interaction accessible by visual or aural observation fit in a given framework. Yokoyama (1986) adds that the "sharing of information is a prerequisite for discourse," and this shared system must include the knowledge of a linguistic code utilized by the embedded speech community and a repertoire of semiotic and biosemiotic systems (p. 24).

Biosemiotic resources include the use of sign processes and sign relations between and within bodies (Favareau, 2010). Douglas (1982) denotes the body as a system of “natural symbols” that reproduce the complexities of our social world. Therefore, it constitutes the way in which communication, meaning, and action are constituted and done within face-to-face interaction. The participants’ shared referential environment along with collaborative construction of meaning is achieved by means of verbal (or signed) communication and the decodification of non-verbal events in progress. In this sense, there is a moment-by-moment building of both action and its understanding through the intertwining of both talk with its language structure and embodied resources. Through interaction, different participants can contribute different materials to the emerging structure of the action in progress, and through this process, the action itself can undergo continuous change. Goodwin (2000) explains that “talk and gesture mutually elaborate each other within (1) a larger sequence of action and (2) an embodied participation framework constituted through mutual orientation between speaker and addressee” (p. 1499).

Nevertheless, the scope of a large number of studies of talk-in-interaction is still bound by the limits of visually and aurally accessible information. However, the internal bodily regulation contributes to the ongoing interaction with equally relevant influential resources, informed by the autonomic nervous system, the endocrine system, and the control mechanisms for musculoskeletal activity. Therefore, in order to provide a complete description of the mechanics of social behavior, one must also take into account the physiological functioning of such embodied minds.

The embodied mind thesis holds the principle that the nature of the human mind is greatly determined by the limits and shape of the human body. In support of this concept, Lakoff (1999) claims that the human mind is embodied and that human cognition and abstract reasoning depend on and make use of the sensorimotor system and emotions. Furthermore, the study of embodied cognition is based on the tenet that all aspects of cognition are shaped by aspects of the body, from mental constructs to human performance on cognitive tasks. Such aspects of the body include a perceptual system of the situated environments built into the body and the brain. Furthermore, Gibbs (2005) describes embodiment of cognition as the process of understanding the role of our own body in its everyday environment. Thus, in Gibbs’s version of embodied perception, the individual’s conscious experience of their own physical activities plays an especially important role in structuring their cognitive processing. Lakoff and Gibbs seem to suggest that psychophysiological aspects of embodiment are part of the human condition and behavior; thus, studies of social engagement behaviors in applied linguistics, education, sociology, anthropology, psychology, and communication studies must consider the information derived from bodily responses to changes in the environment in the analysis of an interactive event.

Applied linguists might also be interested in investigating the underlying emotions that correlate with a research participant's turn in a conversation, how their heart rate and respiration patterns affect their pitch, voice volume, or length of turns; they might also be interested correlations between the cognitive load of a language task with variations in participants' heart rate, pupil dilation, and skin conductance. This is because research has shown that there are certain measurable changes in autonomic responses that correlate with the cognitive load of a language task, such as reading a text or taking a test; correlations have also been found with other aspects of language performance, such as with test performance anxiety (Burov & Tsarik, 2012). Traditionally, those who study human emotions and measure their correlations to human experiences and activities make use of psychophysiology, which is the branch of psychology that is concerned with the physiological bases of psychological processes.

Psychophysiology can offer insightful information about language use. Let's use turn-taking as an example. Turn-taking is a fundamental part of any conversation. Turn-taking requires a collective understanding of whose turn it is, who is going to speak next, and when the right moment to take a turn is (Sacks, Schegloff, & Jefferson, 1974). Because speakers share the knowledge of the conventions of turn-taking behavior, they can successfully negotiate how long they can hold the floor, how they should frame their contributions to make them relevant to the conversation and to other participants, or when it is appropriate to change the topic of an ongoing conversation. But such mutually agreed interactional behaviors are also largely influenced by the speakers' willingness to take the floor or keep it, to share their thoughts and experiences with others, or to reveal their own positionality in regards to the topic being discussed. In other words, speakers' participation and performance in a conversation or discussion are not only influenced by the situational context and nature of the turn-taking engagement, but they are also directly influenced by the speakers' psychophysiological traits and states (Cacioppo, Tassinary, & Berntson, 2016; Quintana et al., 2012; Thayer et al., 2012).

A language user's willingness to contribute to a conversation can definitely affect the turn-taking dynamics of a linguistic exchange. *Willingness* is a psychological construct, and its importance in language production and language learning has been amply documented in the second language acquisition (SLA) literature. In fact, a well-known scale used in SLA research designed to measure the effect that psychological constructs have on communicative performance is the Willingness to Communicate scale or WTC. It was first developed by McCroskey and Baer (1985), and it compiled a number of underlying psychological factors that can increase or decrease a person's willingness to engage in a conversation when the opportunity presents itself (MacIntyre, Clément, Dörnyei, & Noels, 1998). WTC was originally conceptualized as a personality-based predisposition to speak that included a hierarchy of antecedents starting with personality traits and moved toward more communication-related state variables, like Communication Apprehension and Perceived Competence (MacIntyre, 1994; MacIntyre, Babin, & Clément, 1999; MacIntyre & Doucette, 2010; McCroskey & Baer, 1985; Robson, 2015). SLA literature often discusses the fundamental role of ample practice in order to become proficient in a language; the amount of practice that a language learner gets is believed to be positively correlated with the occurrences of opportunities for practice, which varies tremendously depending on the learner's access to communicative exchanges in the target language. But it is evident that one must also consider the psychophysiological dimension of this claim. Simply increasing learners' opportunities to practice the target language is not sufficient to improve their language proficiency. They have to be willing to make use of those opportunities. This example illustrates the complex nature of language learning, and it also points to the importance of taking into account psychological factors, which can be measured with psychophysiological methods.

In order to record psychological data such as language users' willingness to communicate, researchers need to make use of well-designed and validated psychological scales and survey. In order to capture physiological data, researchers have to make use of ambulatory and biometrics technology. For instance, neurolinguists have made major contributions to our current understanding of the neural mechanisms that underlie language acquisition, comprehension, and production by making use of functional resonance magnetic imaging, computed tomography scans, electroencephalography, magnetoencephalography, event-related potentials, and near-infrared spectroscopy in combination with eye-tracking devices (Knoeferie & Crocker, 2010). They have also been able to examine learners' emotional stability when performing learning tasks under internal and external stress by incorporating physiological measures such as electroencephalograms, heart rate, and blood pressure (Burov & Tsarik, 2012). For example, a study conducted by Williams (1987) exemplifies how psychophysiology can provide information with important implications in language research and pedagogy. He used electromyography to examine whether covert linguistic behavior was related to writing performance among college undergraduates. The findings demonstrated a significant correlation between EMG response and lack of writing skill. There were measurable psychophysiological differences between the two groups for both reading and writing tasks. The remedial study subjects manifested higher electromyography readings while writing, but lower ones during pauses compared to the above-average group. These findings had significant pedagogical implications because they suggested that pausing episodes are crucial elements of the composing process and that subvocal motor activity plays a significant role in writing performance.

In an article calling for a closer articulation between theory and measurement in SLA research, Norris and Ortega (2009) propose that language researchers adopt a multidimensional approach. A study conducted by Sun and Zhang (2020) is a great example of how a multidimensional approach can increase our understanding of the development of second/foreign language–speaking abilities. These authors argue that speaking is as a cognitively demanding skill that requires learners to have the ability to not only use various resources ranging from linguistic, pragmatic, to intercultural knowledge, but they also have to deal with anxiety, negative self-efficacy, willingness to communicate, and possibly low levels of motivation, paired with social factors such as interest in the L2 culture. What makes their work particularly multidimensional is that they investigated cognitive, affective, and sociocultural factors as contributing or hindering variables in learners' L2 speaking development, in order to investigate how these three dimensions work together to influence individuals' L2 speaking performance. This example shows us that in order to achieve measurable multidimensionality, language research must be transdisciplinary. Sun and Zhang (2020) were able to assess cognitive, affective, and sociocultural variables and correlate that data to their L2 speaking development, but they would have been able to measure the constructs of the cognitive and affective domains more accurately had they recorded psychophysiological data as well.

It is through the combination of linguistic performance data with participants' sociocultural, cognitive, affective, psychophysiological characteristics that several modalities of data can be juxtaposed and a multidimensional approach to research can take shape. A number of studies in SLA have already used a variety of multidimensional combinations of data in their research designs in order to assess the depth of complexity of language learning models and constructs (Ellis, 2016; Kuiken, Vedder, Housen, & De Clercq, 2019). But for decades, applied linguists proposed—and then rejected or criticized—incomplete and untested language learning models and theories. The experience acquired through the evaluation of such models and theories failed to explain discrepancies found when studies of language learning and performance were reproduced in different context and with different learners, which naturally yielded different results. Language researchers today have a better appreciation of the complexity of SLA. In fact, it has been posited that language learning resembles a complex adaptive system (Larsen-Freeman & Cameron, 2008). A complex adaptive system is a system in which a perfect understanding of the individual parts does not automatically convey a perfect understanding of the whole system's behavior. In complex adaptive systems, the whole is more complex than its parts, and more complicated and meaningful than the aggregate of its parts. Thus, it is clear that a methodological approach that aims to better describe this complex system needs to make use of a multidimensional and multimodal approach to research.

The language acquisition process of a single individual can be influenced by a large number of mutually interacting variables of cognitive, affective, sociocultural, and physiological nature. One example of an individual physiological characteristic that affects language learning is age. The age of language acquisition determines how well an individual is likely to learn that language because it has been shown that certain linguistic features have a critical period to be acquired, after which native-like language acquisition becomes more challenging. This is the central belief of the critical period hypothesis (Lenneberg, 1967), which posits that up until the beginning of puberty, individuals are likely to acquire language skills comparable to those of native speakers (Birdsong & Molis, 2001). However, and despite the variety of studies supporting the critical (or sensitive) period hypothesis, the assertion that it is impossible to achieve native-like proficiency after puberty has been challenged because there have been enough evidence indicating that adult learners can obtain native-like language proficiency in a second language. While some interpret these exceptional outcomes as evidence that disproves the critical period hypothesis (Mayberry & Kluender, 2018), others attribute them to the rare success of certain language learning conditions that allow the achievement of native-like language proficiency at a later age; these could be the presence of above-average levels of language aptitude (Abrahamsson & Hyltenstam, 2008), or higher cognitive abilities paired with increased exposure to the target language (Kalter, Kogan, & Dollman, 2019). For example, a study conducted by Dollman, Kogan, and Weibmann (2019) showed that the strength of the foreign accent of immigrant adolescents in Germany was inversely correlated with their age. These authors demonstrated that the critical period to learn the German phonological system was up to the age of 10, after which obtaining oral language skills without a foreign accent became less common. But they also found that native-like language skills can be achieved after the critical period if certain preconditions related to learning efficiency and language exposure are met, such as higher cognitive abilities and exposure to a language environment with intensive and repeated contacts with native speakers in order to compensate for the disadvantages caused by a late start in their SLA. In general, SLA among children is understood to draw on neurolinguistic processes that are different from SLA among adults. Consequently, psychophysiological research has the potential to provide additional insights.

What makes age an important factor in SLA research is the fact that it is correlated with brain maturation. Although infants learn their first language alongside their cognitive development, adults may be faced with the challenge of having to learn a second language later in life. The differences and commonalities existing between the acquisition process in infants and the learning process in adults might shed some light on the learning machinery necessary for mastering a new language. It is clear that important neurophysiological factors that differ between the two populations may impact the way learning takes place. In that sense, infants are making sense of a whole world while developing other cognitive functions in conjunction with language. Moreover, this development in infants is accompanied by different rates of brain maturation and myelinization in different brain regions, which constrains cognitive functions. These maturation factors add to other aspects such as implicit learning (non-instructed) of first language acquisition, as compared to the frequently explicit training in adult second language learning. Nevertheless, aside from these factors, some core aspects of language acquisition might be shared between the two populations. Thus, a complementary methodological approach to the comparison of both child and adult language learning mechanisms must take into account neurobiological and developmental perspectives. For example, noninvasive acquisition of brain activity (e.g., using event-related brain potentials and structural and functional magnetic resonance imaging) and the study of the developmental changes that occur in the course of language learning or language performance (at the structural and functional brain levels) can prove to be a very useful aid in filling in the missing pieces of information about language learning mechanisms in infants and adults.

Another area of language research that has already benefitted from a multidimensional and transdisciplinary approach to research and from psychophysiological methods is the study of the neurobiological factors that differentiate monolingualism from bilingualism. In contrast to the acquisition of a first language, the successful learning of a second language depends on multiple variables. Second language learners vary along some fundamental dimensions such as age of acquisition, amount of exposure and opportunities to practice, motivation, the type and setting of the learning experience, and also the degree of similarity between their first and the second languages. As it takes place later in a person's life, second language learning affords the opportunity to test relevant issues about learning and brain plasticity, such as the presence of critical periods; however, it also causes crucial methodological difficulties, such as finding homogeneous study groups in which individuals share equivalent socioeconomic, linguistic, and psychophysiological characteristics. This variability across second language learners is particularly relevant for neuroimaging studies that typically involve relatively small samples, and thus can be more affected by heterogeneous sampling.

How bilinguals represent and manage their two linguistic systems is a core issue in bilingualism. Recent studies have explored the neural representations that differentiate this group of learners from monolinguals. It has been shown that certain linguistic representations and processes seem to be shared across languages and that the first and second languages are active in parallel in most contexts (Hartsuiker, Pickering, & Veltkamp, 2004). Indeed, similar brain structures are involved when bilinguals use either of their two languages (Perani et al., 1998). However, the degree of neural overlap between the two languages depends primarily on the speaker's second language proficiency and, to some extent, on age of acquisition of the second language (Kotz, 2009), which is nonetheless consistent with the convergence hypothesis (Green, 2003), which states that the neural networks involved in language acquisition and processing are similar for the first and second language. However, there is also evidence suggesting that some language-control brain areas are differentially recruited in the first language and second language, often attributed to a more effortful processing of second language rather than to differences in the actual representation of the two languages (Luk, Green, Abutalebi, & Grady, 2012). For example, a study conducted by Costa and Sebastian-Gallés (2014) describes how becoming bilingual affects first language processing and executive control processes. They argue that the main differences between monolinguals and bilinguals in terms of language acquisition and processing are rooted in two factors: (1) that bilinguals receive less exposure to and make less use of each of their languages than monolinguals do in their only language, and (2) that bilinguals need to monitor their language systems in a more demanding way than monolinguals, requiring the involvement of cognitive control structures. These authors explain that these two features increase the processing demands during bilingual language acquisition and processing. Thus, while the neural networks involved in first language processing seem to be fundamentally the same for monolinguals and bilinguals, the latter group faces higher processing demands that lead to an increase in brain activity. Costa and Sebastian-Gallés (2014) add that coping with this increase in processing demands creates a boost in executive control abilities, which starts in infancy and continues throughout the life span, possibly enhancing cognitive reserve in the elderly.

In sum, psychophysiological research methods have been widely used in social psychology since the 1960s, and it is a well-established approach to the scientific investigation of underlying emotional regulation processes during linguistic and cognitive tasks as well as to study social engagement behaviors. However, for decades, psychophysiological methods imposed a few limitations to experimental in-lab procedures: first, it had to take place at a psychophysiology lab, where all the equipment was kept; second, it required that study participants wear a combination of ambulatory monitors to record physiological changes via electrodes attached to their heads, hands, chest, fingers, or other parts of the body, which were then connected to receivers, transmitters, and computers during. Such sterile setting certainly did not resemble a naturalistic environment, potentially altering participants' psychophysiological states; third, because of potential artifacts that participants' body movements could superimpose on the data, they would be told to refrain from crossing their legs, standing up, or moving their arms—among others—during the recordings.

Current technology has improved the quality of data output; it has become considerably more affordable, and has allowed hours of continuous recording of physiological changes away from the lab setting, along with freedom of movement. Modern data acquisition systems support multiple channels with differing sample rates at speeds up to 400 kHz, and online monitoring of physiological activity, with the choice of both wired and wireless signal-specific amplifiers. For example, with a 16-channel data acquisition system, a researcher can monitor and record 2 physiological measures of a group of 8 participants, simultaneously. What's more, such modern physiological equipment allows researchers to combine functional neuroimaging with other forms of psychophysiological measurement, including autonomic monitoring, providing an empirical basis for understanding brain–body interactions. Moreover, wireless and wearable devices give researchers more freedom to choose settings outside of the lab, design more complex experiments, or more importantly, let participants move more freely and naturally. Many data acquisition systems also come with their own native software that displays, controls, analyzes, replays, and exports data.

Information obtained from psychophysiological data has proven to be quite reliable, so research on language users' performance and learning through the lens of their underlying psychophysiological profile and autonomic states has proven to be productive. Therefore, it is clear that psychophysiological measures in studies of language performance can yield valuable information. However, the challenges posed by bridging transdisciplinary methods in language research cannot be ignored. Among others, these would be that (1) information obtained from multiple modalities of data collection methods requires a system that supports the analysis of multimodal data in conjunction with the observed behavior; (2) this potentially vast amount of data processing will most likely yield correlational information, not causal; and (3) the correct interpretation of data requires training and precise application of selected methods. The latter can be achieved by either collaborating with colleagues from across different disciplines or through furthering one's transdisciplinary methodological knowledge and training. One must always keep in mind that if correct measurement, data processing, and interpretation are not done correctly, the data gathered will be meaningless, and their hard work, fruitless.

This book's intended audience is the researcher who wants to adopt a multidimensional approach to the investigation of language learning, language teaching, language use, language assessment, language performance, language anxiety, and language attitude, ideologies, perceptions, and motivations. Deciding on suitable data collection mechanisms that can yield relevant information about one's research interests requires familiarity with the required measurement instruments. When it comes to psychophysiological measurement devices, the researcher must consider the research setting, the participants, the task or experiment, the kind of information that the data obtained can provide, the amount of time required to gather the data, resources already available, practicality, budget constraints, and availability of required psychophysiological instruments.

Because deciding on a suitable physiological measurement method that can yield relevant information about one's research interests requires familiarity with the said method, the purpose of this book is to provide a broad overview of each of the most popular physiological measurements today, along with their potential applications in language research. More specifically, the goal of this book is threefold: (1) to explain what each of the selected physiological methods can tell us; (2) to illustrate how each physiological method can inform language research by citing a few language studies that used that particular measurement; and (3) to offer the reader basic information about the appropriate procedures for data collection and data processing before data analysis can be conducted.

Finally, this book is organized in the following manner: chapter 1 talks about the basic principles and conceptual theories that support the use of psychological and physiological measurement in social behavior and language research; and chapters 2 through 10 provide an overview of the information retrievable from various psychophysiological measurement methods, examples of language research studies that made use of them, and recommendations to properly collect and process data.

Chapter 1

Describing Emotions

A discussion about the meaning, classification, and measurement of emotions must start from distinguishing emotions from two other similar concepts, namely *feelings* and *moods*. Emotions are induced by chemicals, that is, hormones and neurotransmitters (e.g., endorphins, dopamine, serotonin, glutamate, epinephrine, norepinephrine, cortisol, oxytocin) released throughout the body in response to a person's interpretation of a specific stimulus, also known as a *trigger*. This trigger-response process takes place very quickly. It takes the human brain about a fourth of a second to identify the stimulus trigger and about another fourth of a second to produce and release the chemicals, initiating a feedback loop between the brain and the body. Emotions are modulated by the release of different chemicals in the brain, but there is no one specific chemical for each specific emotion, like a chemical for *love* or for *hate*.

In addition, at any given moment, dozens of hormones and neurotransmitters are active. Some of these neurotransmitters go between individual cells, while others are broadcast to entire brain regions. By layering signals on other signals, the brain can adjust how a person responds to information received from sensory inputs. For example, when a person perceives danger, their brain releases stress hormones that make them react faster, flooding certain regions with the neurotransmitter epinephrine (also known as adrenaline, an excitatory neurotransmitter). When the danger subsides, the brain sends out a calming signal in the form of inhibitory neurotransmitters that dampen the response of the regions that create fear. Fear is a basic emotion shared by all mammals, just like the emotion *anger*. But humans have especially highly developed social emotions, such as *shame*, *guilt*, and *pride*, which involve an awareness of what other people think and feel about us.

Feelings are different from emotions. Feelings happen as the individual begins to integrate the emotion, to think about it, to reflect on it. Another way to describe this concept is to think about examples of how the verb “feel” is used in English for both *physical* and *emotional* sensation. A person can say that they “feel cold,” and it can mean *physically* or *emotionally*, indicating that a feeling can be related to a physical or emotional sensation. Feelings are more cognitively saturated as the emotion chemicals are processed in an individual’s brain and body. Feelings are often fueled by a mix of emotions, and last for longer than emotions.

Finally, *moods* are more generalized than emotions or feelings. They are not tied to a specific incident, but they can be the result of a collection of inputs. Moods are heavily influenced by several factors like the environment (weather, lighting, nearby people), physiology (diet, exercise, general health), and mental states (focus of attention, current emotions). Moods can last minutes, hours, or even days.

In sum, all humans experience moods, feelings, and emotions. Emotions influence action, thoughts, and behavior, but most importantly, they are believed to be the result of a selective adaptation that ensures survival (Darwin, 1872). This survival adaptive behavior is a multistep process that observes the following chain of events (see figure 1.1):

As can be seen in figure 1.1, the brain gets information from one or more sensory input (from vision, audition, olfaction, or touch). Sensory inputs inform the brain of what is going on in the outside world, and the person’s preexisting emotional states and somatic markers (Damasio, 1996) along with the social context, personal traits, and mood assist in the interpretation of those external events and circumstances. Sensory input from the external environment plays an important role in how a person feels and behaves. Environmental characteristics such as the brightness of light sources, the nature and level of ambient noise and acoustics, the presence of specific odors, color hues and shades, and materials and atmospheric factors such as temperature and humidity, all generate sensory input, and combined contribute to specific reactions in the observer (Schreuder, van Erp, Toet, & Kallen, 2016). In addition, the impact of sensory input on behavior is not only based on sensory cues but also on the social context, personal traits, and mood of the observer. For instance, an excited person perceives odors as more intense, has a more limited field of view, and perceives sounds more selectively. People on deserted railway platforms feel safer when light intensities are high and when stimulating music is played, whereas on crowded platforms the same measures increase stress levels. Also, patients treated in a room with white walls (compared with green walls) disclose more information and have more faith in their practitioner, whereas rooms with green walls may increase patients’ stress levels (Schreuder, van Erp, Toet, & Kallen, 2016).

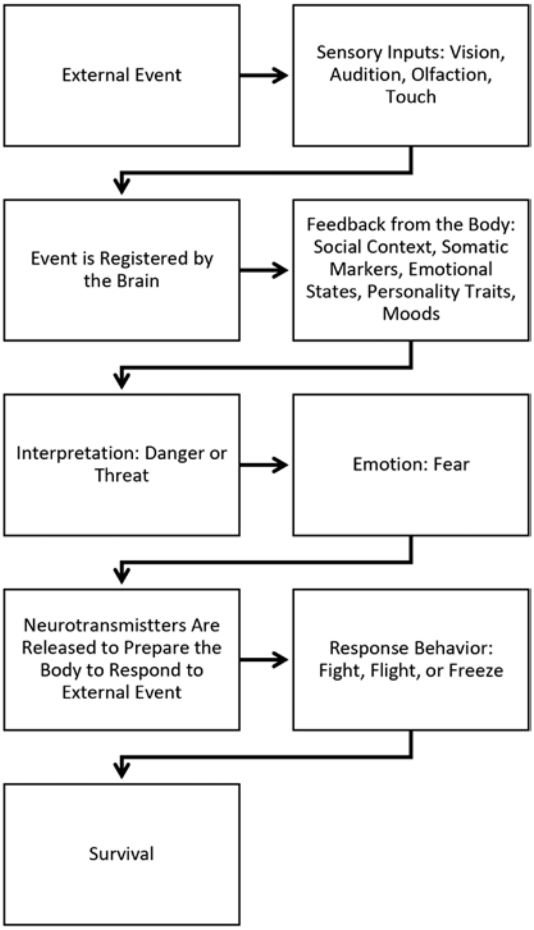

Figure 1.1 A Multistep Survival Adaptive Behavior Linking External Event to a Response Behavior. *Source*: Diagram created by author.

Environmental stimuli go through lower-order processes and higher-order processes. The first processing steps of environmental stimuli are done through a person's senses and the primary sensory areas in our brain, being automatically and unconsciously, thus without conscious intervention or interpretation. These are lower-order processes, and the primary structures involved are the lower brainstem networks, diverse limbic structures (e.g., the amygdala interacting with the hippocampus), and the basal ganglia. This processing level results in the sensation of environmental stimuli.

In addition to the automated lower order processes, higher order processes (which include previous experiences, information stored in memory, and somatic markers) are involved through the hippocampus and temporal cortical structures to integrate, and they perceive the sensory information (O'Callaghan, 2012). The influence of higher-order processes depends on factors such as attention and the processing capacities of the person at that time. This processing level involves conscious as well as unconscious processing. The integration and interpretation of the sensory information results either in a holistic perception of an object or environment or in an emotional experience (Barrett et al., 2013).

BASIC EMOTIONS

Many theories of emotion basicality have been proposed, with contrasting views. Some of them are listed here. The first publication worthy of mention in this section was an essay titled "What Is an Emotion?," by William James, published in 1884. James made a revolutionary case for acknowledging that much of our mental life is intertwined with our physiology. He proposed four basic emotions: *fear*, *grief*, *love*, and *rage*, based on distinct bodily expression each one of them conveyed. He believed that physiological changes follow the perception of a stimulating event and that our feeling of those changes as they occur is the emotion.

Paul Ekman and his colleagues, in a cross-cultural study published in 1992, identified six basic emotions, which they identified on the basis of their distinct facial expressions: *anger*, *disgust*, *fear*, *happiness*, *sadness*, and *surprise*. Ekman later proposed an expanded list of emotions, including a range of positive and negative emotions that are not all encoded in facial muscles. These were *amusement*, *contempt*, *contentment*, *embarrassment*, *excitement, guilt, pride in achievement*, *relief*, *satisfaction*, *sensory pleasure*, and *shame*. These emotions were called secondary emotions as they result from a combination of the primary ones (e.g., *anxious* (primary) + *sad* (primary) = *shame* (secondary)) (Ekman, 1999).

Richard and Bernice Lazarus (1996) expanded the list of known emotions to a total of 15, which were the following: *aesthetic experience*, *anger*, *anxiety*, *compassion*, *depression*, *envy*, *fright*, *gratitude*, *guilt*, *happiness*, *hope*, *jealousy*, *love*, *pride*, *relief*, *sadness*, and *shame*.

Robinson (2009) studied fundamental emotions by examining their underlying brain functions, emotional experience, and personality descriptors. He believed that basic emotions must observe three key criteria: they are mental experiences that have a strongly motivating subjective quality like *pleasure* or *pain*; they are a response to some event or object that is either real or imagined; and they motivate particular kinds of behavior. He believed that the combination of these attributes distinguishes emotions from sensations, feelings, and moods. Robinson categorized emotions as positive or negative, and grouped them in the following manner: those related to object properties (as in *interest* or *indifference*); those related to future appraisal (as in *hope* or *dread*); those related to event-related (as in *gratitude* or *disappointment*); those related to social behavior (as in *sympathy* or *arrogance*); and those that are cathected (as in *love* or *hate*).

Using 2,185 short videos intended to elicit emotions from viewers, Cowen and Keltner (2017) increased the list to 27 emotions: *admiration*, *adoration*, *aesthetic appreciation*, *amusement*, *anger*, *anxiety*, *awe*, *awkwardness*, *boredom*, *calmness*, *confusion*, *contempt*, *craving*, *disgust*, *empathic pain*, *entrancement*, *excitement*, *fear*, *horror*, *interest*, *joy*, *nostalgia*, *relief*, *romance*, *sadness*, *satisfaction*, *sexual desire*, and *surprise*.

All in all, humans' subjective experience is that emotions are clearly recognizable in ourselves and others. This apparent ease of recognition has led to the identification of a number of emotions that are said to be *basic*, and universal among all people. However, a debate among experts has questioned this understanding of what emotions are (Gendron & Barrett, 2009).

On *basic* emotion accounts, activation of an emotion, such as *anger*, *sadness*, or *fear*, is triggered by the brain's appraisal of a stimulus or event with respect to the perceiver's goals or survival. In particular, the function, expression, and meaning of different emotions are hypothesized to be biologically distinct from one another. A theme common to many basic emotion theories is that there should be functional signatures that distinguish different emotions: an observer should be able to tell what emotion a person is feeling by looking at their brain activity and/or physiology. Furthermore, knowledge of what the person is seeing or the larger context of the eliciting event should not be necessary to deduce what the person is feeling from observing the biological signatures (Ekman, 1992).

On *constructionist* accounts, the emotion a person feels in response to a stimulus or event is constructed from more elemental biological and psychological ingredients. Two hypothesized ingredients are *core affect*, which is characterized by valence and physiological arousal, and *conceptual knowledge*, such as the semantic meaning of the emotion labels themselves (e.g., the word *anger*). A theme common to many constructionist theories is that different emotions do not have specific locations in the nervous system or distinct physiological signatures and that context is central to the emotion a person feels because of the accessibility of different concepts afforded by different contexts (Barrett, 2006).

Emotions have also been shown to have a social function. They provide information about others' behavioral intentions, influence people's social behavior (Eisenberg, 2001; Gross, 1998; Keltner & Kring, 1998), facilitate responses to situational challenges (Tooby & Cosmides, 1990), and maintain mental health (Gross & Munoz, 1995).

Although the categorization of emotions has been the subject of much debate, most theorists agree on three basic tenets: that emotions are complex, that they involve coordinated changes in peripheral and central physiology, and that they are related to behavior or behavioral tendencies and cognitive processing. Several studies have shown that emotions are physiologically functional (Damasio, 2000, 2003) because they have a facilitating function in decision-making and preparing an individual for fast motor responses. From this perspective, emotions are adaptive responses to the environment, and those which are modulated with sensitivity to the situational context in terms of timing, occurrence, and magnitude are more likely to facilitate adaptive responses.

CULTURAL CONSIDERATIONS

Ethnographic and cross-cultural studies of emotions have shown the variety of ways in which emotions might differ with cultures. Because of these differences, many cross-cultural psychologists and anthropologists challenge the idea of universal classifications of emotions.

Cultural differences have been observed in the way in which emotions are valued, expressed, and regulated. The social norms for emotions, such as the frequency with or circumstances in which they are expressed, also vary drastically (Ekman, 1991; Mesquita & Nico, 1992; Russell, 1991). For example, the demonstration of anger is encouraged by Kaluli people, but condemned by Utku Inuit people (Eid & Diener, 2001).

The largest piece of evidence that disputes the universality of emotions is language. Languages differ in that they categorize emotions based on different components. Some may categorize emotions by event types, whereas others categorize them by action readiness. Furthermore, emotion taxonomies vary due to the differing implications emotions have in different languages. For example, not all English words have equivalents in all other languages and vice versa, indicating that there are words for emotions present in some languages but not in others (Wierzbicka, 1986). Emotions such as the *schadenfreude* in German and *saudade* in Portuguese are commonly expressed in emotions in their respective languages, but lack an English equivalent. Some languages do not differentiate between emotions that are considered to be the basic emotions in English. For instance, certain African languages have one word for both *anger* and *sadness*. There is ethnographic evidence that even challenges the universality of the category *emotion* because certain cultures lack a specific word equivalent to this word (Russell, 1991).

THE ROLE OF EMOTIONS IN LANGUAGE RESEARCH

Emotional regulation has had an important role in communication and social research (Clough & Halley, 2007; Döveling, von Scheve, & Konijn, 2011; Frijda, 1986; Nabi, 2010). For example, some studies in these areas have investigated the role of emotions in information processing (Nabi, 2009; Konijn & ten Holt, 2011). Other studies have shown that emotion and attention are strongly connected (Ohman, Flykt, & Esteves, 2001); that negative messages capture more attention than positive ones (Bolls, Lang, & Potter, 2001); that increased emotional arousal results in better storing of messages in long-term memory (Lang, Newhagen, & Reeves, 1996); that persuasive messages are more convincing if they are emotionally arousing (Gresham & Shimp, 1985; Hazlett & Hazlett, 1999); and that in online communications settings, any content or application that elicits positive emotions is most likely preferred (Ravaja, 2004). Physiological recordings have also been used to study the changes elicited by the receipt of news messages (Ravaja, Saari, Kallinen, & Laarni, 2006; Grabe, Lang, Zhou, & Bolls, 2000), as a response to slow websites (Sundar & Wagner, 2002), and to explore marketing information processing and economic decision-making (Braeutigam, 2005; Lee & Chamberlain, 2007; Rossiter, Silberstein, Harris, & Nield, 2001).

One specific example of a study that looked at the effects of emotions on language processing is a study conducted by Jimenez-Ortega et al. (2012). These authors investigated how a paragraph of positive, negative, or neutral emotional valence affects the processing of a subsequent emotionally neutral sentence, which contained semantic, syntactic, or no violation, respectively, by means of event-related brain potentials (ERPs). The behavioral data that they obtained revealed strong effects of emotion; error rates and reaction times increased significantly in sentences preceded by a positive paragraph relative to negative and neutral ones. In the syntactic experiment, they found clear emotion effects on ERPs. They also found reflecting modulatory effects of prior emotions on syntactic processing, which they related to three explanations involving emotion-induced cognitive styles, working memory, and arousal models. These three dimensions of mental and emotional processing are measurable via recordings of autonomic psychophysiological responses.

AUTONOMIC PHYSIOLOGICAL RESPONSES THAT INDICATE EMOTIONAL STATES

The regulation of emotions depends critically on an individual's ability to adjust their autonomic physiological response on a momentary basis (Gross, 1998). A *flexible* autonomic nervous system allows for fast modulation of physiological and emotional states based on situational demands, whereas autonomic *rigidity* results in a diminished capacity to alter physiological and emotional responses in reaction to changes in the environment. Joseph LeDoux (1998) described emotions as fast, automatic, and stereotyped responses of an individual to a situation that can be potentially significant to that individual's survival. According to LeDoux, the perception of an affective stimulus activates two neural pathways that are independent but interconnected: one that is unconscious and that activates peripheral reactions, and another one that is conscious and that produces cognitive awareness of emotion.

One of the neural centers related to the unconscious perception pathway of an affective stimulus is the amygdala, which is where the first process of the stimulus is made. Located in the temporal lobes of the brain, the amygdala is part of the limbic system, and it is composed of a large cluster of around thirteen nuclei, which are subdivided into smaller complexes. The basolateral complex is the largest of these subdivisions and is composed of the lateral nucleus, basolateral nucleus, and accessory basal nucleus. This nuclei complex has connections with the cerebral cortex, thalamus, and hippocampus. Nuclei of the amygdala also make connections with the hypothalamus and brainstem. While the hypothalamus is involved in emotional responses by preparing the body for vigorous physical activity through the regulation of the endocrine system (Owen et al., 2006), the brainstem relays information between the cerebrum and spinal cord. Thus, connections to these areas of the brain allow amygdaloid nuclei to centralize and process information from sensory areas (cortex and thalamus) and activate areas associated with behavior and autonomic function (hypothalamus and brainstem) (Kallat, 2007). Thus, through the amygdala, the peripheral response activation is emotion-specific even before the realization of conscious experience. This mechanism is important in an evolutionary context because by considering a potentially dangerous stimulus, this unconscious response system triggers safety adaptive responses. However, if moments later and after the conscious processing of a stimulus, it is determined that it is not dangerous, then the unconscious emotional system falls rapidly to the basal (normal) state. But if the situation is indeed appraised as being dangerous, the activation of the emotional response is retained and maintained.

A quick response to a potentially dangerous situation can ensure an individual's well-being and even survival. For this reason, it is necessary for the body to react as quickly and efficiently as possible. To make this possible, physiological responses must be automatic and subsequently stereotyped. A stereotyped response is one that is identical or very similar in different situations in which the same emotion is experienced.

Emotional states have been shown to correlate with physiological changes, and the strategies that elicit physiological changes during an experiment are physical stress, cognitive stress, anxiety-inducing tasks, humor, and imagery, among many others (Cacioppo, Klein, Berntson, & Hatfield, 1993; Ekman & Davidson, 1994). For example, anger imagery has been shown to trigger the largest effects on the cardiovascular system, compared to fear, joy, or sadness (Sinha, Lovallo, & Parsons, 1992). Physiological changes can be correlated with positive and negative emotions via facial electromyography, for example (Cacioppo, Petty, Losch, & Kim, 1986). During electromyography measurements, increases in the activation of the cheek (zygomaticus major) muscle area have been associated with positive emotions, whereas increases in the activation of the brow (corrugator supercilii) muscle region have been associated with negative emotions (Witvliet & Vrana, 1995). Periocular muscle area activity has been shown to be particularly high during positively valenced high-arousal emotions (Ravaja, 2004).

An example of a cognitive ability that is very relevant in language research and that can employ physiological recorders is *attention*. Attention is more than just noticing a particular stimulus. It involves a number of processes including filtering out distractions, balancing multiple sensory information from the environment, and attaching emotional significance to these perceptions. Attention can be either passive or active. Whereas passive attention refers to the involuntary processing of external events that stand out from the environment such as a sudden noise or a bright flash of light, active attention is voluntary and is modulated by alertness, concentration, and interest. Therefore, active attention is a multidimensional cognitive process that includes the ability to select and focus on what is important at any given moment, the ability to consistently maintain mental effort, which requires mental energy and the ability to inhibit other actions or thoughts. Active attention can be measured with electroencephalography (EEG). Studies have shown that increased activity in the broad alpha band (8–13 Hz) of EEG is inversely related to neural processing; alpha power decreases when the underlying cortical systems engage in active processing. In addition, frontal alpha asymmetry is a widely used metrics assessing approach/withdrawal motivational behavior (Coan & Allen, 2004), as they are required components of active attention.

The dynamics of the autonomic nervous system reflect measurable changes according to a person's emotional experience (Nasoz, Alvarez, Lisetti, & Finkelstein, 2003; Posner, Russell, & Peterson, 2005). It is also a control system in charge of the regulation of peripheral functions such as heart rate, digestion, respiratory rate, pupillary response, urination, and sexual arousal. The most commonly used indexes of activation of the autonomic nervous system are based on electrodermal activity and cardiovascular dynamics (Valenza & Scilingo, 2014). For example, Lang, Bradley, and Cuthbert (2005) have shown that the level of electrodermal activity increases systematically and linearly depending on the general arousal level of the emotional stimuli. However, some measurements of the activity of the autonomic nervous system can operate in tandem or contrariwise. For example, a reduced heart rate results from an increase in activity of the parasympathetic nervous system, and from a decrease in activity of the sympathetic nervous system (Bradley & Lang, 2000).

Therefore, only through a combination of several measures of the autonomic nervous system can a researcher obtain a more complete description of discrete emotional states. For example, Valenza and Scilingo (2014) showed that anger and fear, despite their alignment in terms of valence and arousal, can be differentiated by a combination of cardiovascular and respiratory measures, and Cacioppo et al. (2000) showed that cardiac output, blood pressure, heart rate and skin conductance respond to emotional valence.

THE POLYVAGAL THEORY

The polyvagal theory explores the role of autonomic function in the regulation of emotions and social behavior (Grippo, Lamb, Carter, & Porges, 2007; Porges, 2001, 2003). It provides a framework for understanding the development of adaptive diversity in homeostatic, threat-response, and psychosocial functions that contribute to social behavior (Porges & Lewis, 2010; Porges, 2011b). The polyvagal theory posits that people get cues from their social environment in order to decide whether or not it is safe to socially engage (Porges, 2009) and that it makes use of a mechanism that mediates the expression and the disruption of positive social behavior, emotion regulation, and visceral homeostasis. The operation of such system can be studied by tracking physiological changes that are triggered by the sympathetic and parasympathetic nervous systems, the two components of the autonomic nervous system (see figure 1.2). Examples of such adaptive responses are pupil dilation, changes in palmar skin conductance, heart rate, respiration, blood pressure, and so on.

Measures of autonomic regulation have been shown to index motivation and arousal, and this fact has a vast utility in the realms of social sciences. For example, a common physiological compass of human emotion is electrodermal activity. Because sweat glands are controlled by the sympathetic nervous system, electrodermal activity has been used as an indicator of physiological arousal. For instance, Shapiro and Leiderman (1967) showed that the mere presence of other persons in the same room during a pre-experimental rest period leads to higher levels of electrodermal activity in the test subject, compared to resting alone. They also showed that arousal can be either increased or decreased depending on the nature of the task (individual or in groups) and

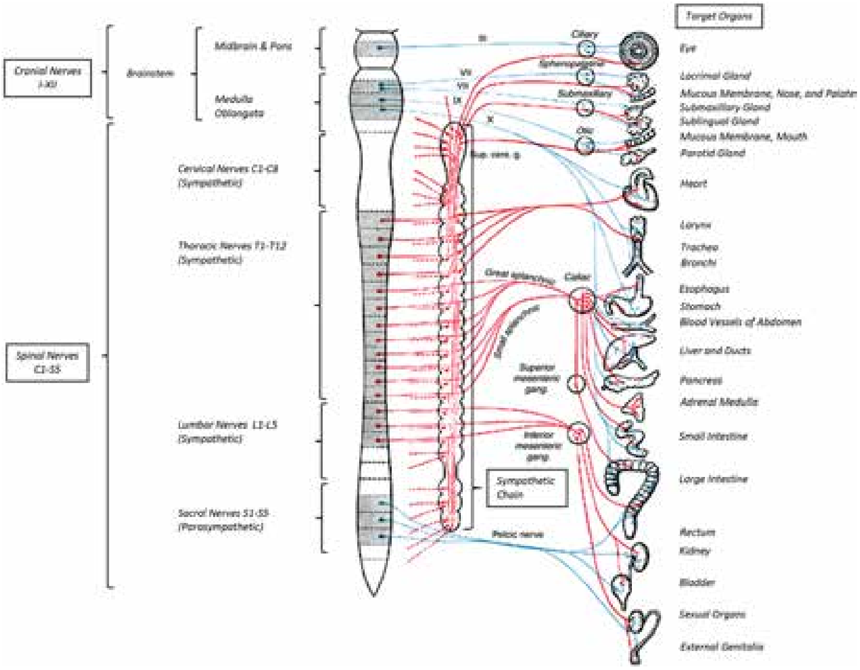

Figure 1.2 Cranial and Spinal Nerves and Their Target Organs. *Source*: Gray's Anatomy Image 839, Public Domain.

on the participants' attitude about a discussion topic, the mutual attitudes of the interacting individuals, the degree to which the individual participates in the task, and the composition of roles within the group.

When interactants use language to socially engage and communicate with others, this communication is not unidirectional following a sequential one-turn-at-a-time system; on the contrary, communication is typically jointly co-constructed by all the involved parties in a collaborative manner, taking into account conversational participants' facial and bodily displays. Such displays are relevant to participants because they provide important information about their underlying emotional states which can relate to the meaning of what is being discussed. Therefore, a multimodal analysis of this interactional structure requires the inclusion of measurements of neurophysiological adaptive responsivity.

Behaviors that take place during ordinary conversation are reflected in measures of physiological autonomic responses. The major components in the maintenance of homeostasis are the central nervous system and the peripheral nervous system. The central nervous system (CNS) is comprised of the brain and spinal cord; the peripheral nervous system (PNS) is comprised of twelve cranial nerves and ganglia outside of the brain and spinal cord (see figure 1.3). The main function of the PNS is to connect the CNS to the limbs and organs, essentially serving as a communication relay going back and forth between the brain and the extremities. Cranial nerve X, also called the *vagus* nerve, is a cranial nerve that carries sensory information between the CNS and visceral organs.

The PNS is divided into the somatic nervous system and the autonomic nervous system (ANS). Together, these two systems are directly responsible for homeostasis. The ANS is formed by the sympathetic nervous system and the parasympathetic nervous system. The former prepares the body for fight or flight, and the latter helps the body go back to its resting state.

The sympathetic nervous system produces the hormone epinephrine. Epinephrine, also known as adrenaline, is a hormone and neurotransmitter. Adrenaline is normally produced by both the adrenal glands and a small number of neurons in the medulla oblongata, where it acts as a neurotransmitter involved in regulating visceral functions. It helps prepare the body to respond to an emergency by increasing heart rate, breathing, or energy transfer to muscles.

The parasympathetic nervous system produces acetylcholine. Acetylcholine is the chief neurotransmitter of the parasympathetic nervous system, and it

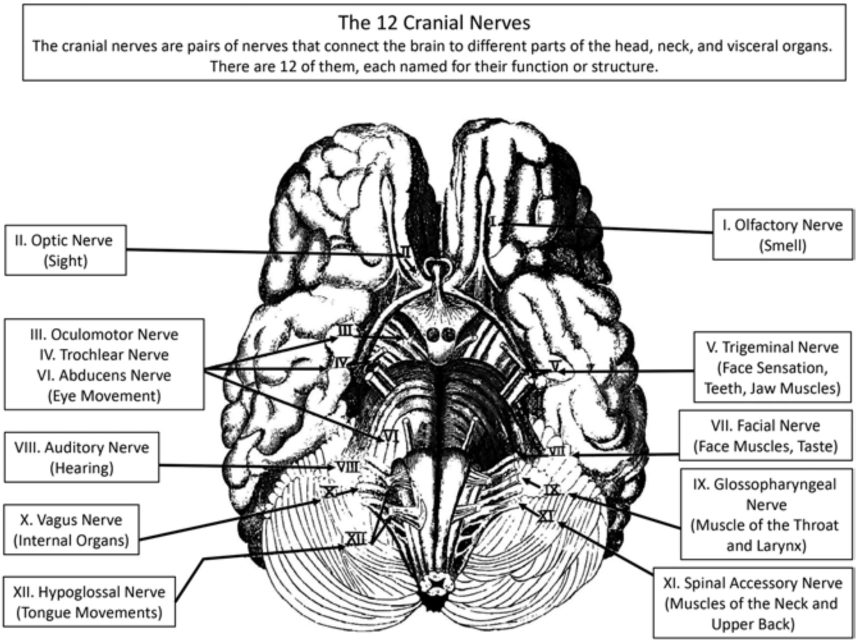

Figure 1.3 The Twelve Cranial Nerves. *Source*: Hill's Manual of Human Physiology Image 192, Public Domain.

is used to calm the body; it contracts smooth muscles, dilates blood vessels, increases bodily secretions, and slows heart rate. In the cardiac tissue, acetylcholine neurotransmission has an inhibitory effect, and it lowers the heart rate. However, acetylcholine also behaves as an excitatory neurotransmitter at neuromuscular junctions in skeletal muscle.

The secretion of adrenaline contributes to the shutdown of all non-vital functions for the duration of the arousal. The bodily reactions to exciting stimuli from our environment that are triggered by the sympathetic system are later regulated by the parasympathetic system, mediated by acetylcholine, a phenomenon known as the *vagal brake* (Porges, 2003). These mutually regulating systems react to stimuli generated in the environment, which are assessed by the CNS, triggering subsequent behavioral and physiological adaptations.

A typical individual is constantly unconsciously and consciously assessing risk in the surrounding environment, and the result of this ongoing assessment is a neurophysiological state that matches this perception. When the environment is appraised as *safe*, the defensive response mechanism is inhibited, calming visceral states and enabling social engagement. According to Porges's (2007) polyvagal theory, social communication can be expressed efficiently through the social engagement system only when the defensive circuits are inhibited. This means that if a certain setting or addressee is perceived as hostile and life-threatening, it is unlikely that the subject will choose to engage in social or communicative behaviors. This reactivity is modulated by temporal cortex responses to the perceived intention of voices, faces, and hand movements. The detection of familiar individuals and individuals with appropriate prosodic voices and warm, expressive faces translates into a sense of safety, promoting social interaction.

Porges's (2007) social engagement system consists of a somatomotor component and a visceromotor component. The somatomotor component involves special visceral efferent pathways that regulate the striated muscles of the face and head, while the visceromotor component involves the myelinated vagus that regulates the heart and bronchi.

Via evolution, the human nervous system retained three neural circuits, which are in a phylogenetically organized hierarchy. In this hierarchy of adaptive responses, the newest circuit is used first; if that circuit fails to provide safety, the older circuits are recruited sequentially (Porges, 2007). A face-heart connection evolved as source nuclei of vagal pathways shifted ventrally from the older dorsal motor nucleus to the *nucleus ambiguus*. This resulted in an anatomical and neurophysiological linkage between neural regulation of the heart via the myelinated vagus and the special visceral efferent pathways that regulate the striated muscles of the face and head, forming an integrated social engagement system.

This social engagement system mediates all our social interactions, whether or not they are perceived as "safe" or "life-threatening." Interactants' decisions on what to say when they next take a turn in the ongoing conversation do not rely exclusively on the current context of the talk, but on the manner in which speech is produced, including pitch, prosody, speed, facial expressions, gestures, bodily displays, epistemic status displays, gaze, and mutual orientations to shared physical and abstract environment.

Functionally, when the social environment is perceived as safe, two important features are expressed. First, the bodily state is regulated in an efficient manner to promote growth and restoration. This is done through an increase in the influence of mammalian myelinated vagal motor pathways on the cardiac pacemaker that slows the heart, inhibits the fight-or-flight mechanisms of the sympathetic nervous system, dampens the stress response system of the HPA axis (e.g., cortisol), and reduces inflammation by modulating immune reactions (e.g., cytokines). Second, through the process of evolution, the brainstem nuclei that regulate the myelinated vagus became integrated with the nuclei that regulate the muscles of the face and head. This link results in the bidirectional coupling between spontaneous social engagement behaviors and bodily states. Specifically, an integrated social engagement system emerged in mammals when the neural regulation of visceral states that promote growth and restoration (via the myelinated vagus) was linked neuroanatomically and neurophysiologically with the neural regulation of the muscles controlling eye gaze, facial expression, listening, and prosody (Porges, 2011).

THE SOMATIC MARKER HYPOTHESIS

Antonio Damasio introduced the Somatic Marker Hypothesis in his seminal book *Descartes' Error*, based on years of research from neurology, psychology, and psychophysiology. Damasio (1994) suggested that all individuals get feedback from their ANS, endocrine system, and musculoskeletal system before displaying a response to a situation or challenge. The Somatic Marker Hypothesis (*soma*, from Greek, means "body") suggests that when something elicits an emotional response from an individual, there are a number of brain-based responses that occur which guide their present and future decision-making; in addition, many of those responses, such as changes in electrodermal activity, are directly measurable indicators of cognitive-emotional processes.

This somatic response informed by feedback from the body provides a basis for how they respond during conversation, and it helps them make social and personal decisions. In ordinary conversational interaction, these decisions are typically unconscious and are informed by the immediate environment, in which the content of the interaction, or what was being said, is emerging through the ongoing calibration and interaction between speaker and hearer. This process encompasses both the interlocutors' talk and their bodies as meaningful canvases for display of action, and sources of experiential knowledge and feedback. Then, it is our understanding that social interactions require an online, two-way, multiparty, second-by-second adaptive process with their neurobiological underpinnings.

In conversational interaction, individuals make both conscious and unconscious judgments about interlocutors' evolving intentions, emotions, beliefs, and behaviors, enabling the interaction to be built through all interpretants' co-participation. Participants' judgments rely on appraisals of the environment, interlocutors, and content of the conversation. Individuals develop such appraisals from monitoring and evaluating one or various occurrence(s) of an event by examining different basic components such as time, expectation, probability, and predictability (Grandjean, Sandler, & Scherer, 2005). Additionally, Schumann's (1999) Stimulus Appraisal System suggests that individuals form and appraise events according to their novelty (i.e., conformity or discrepancy with what is expected), pleasantness, and how they might challenge their ability to cope with the situation. Individuals assess their interlocutor's state of mind and behavior according to whether they foster our goals and enhance our self and social image (Dornyei, 2010). On the basis of these appraisals, they may respond to the evolving interaction in a courteous or aggressive manner, or in a dominant or submissive manner, by manipulating prosody, grammar, and lexicon accordingly, fostering their goals and agendas (Schumann, 1999).

Turn-taking and decision-making in ordinary conversation are far from straightforward, and its analysis should not rely only on the observation of body language, appraisals, emotional expressivity, and talk. There are features that characterize participants' stance and agendas embedded in turn constructions, silences, or tokens of news receipt or disagreements, among many others. For example, Sacks, Schegloff, and Jefferson (1974) suggest that the analysis of turn-taking systems can be done in several ways, and must consider the distribution of talk, distribution of silences, sequences in which the talk shifted from one to another and how it was retained, and so on.

USING PSYCHOLOGICAL SCALES

Psychological tests, scales, questionnaires, and checklists are research tools designed to measure an individual's characteristics on some psychological construct or dimension. It can be responded to by the individual participating in the research or by others, yielding what they call a self-report or other-report, respectively. Self-reports allow respondents to describe their feelings, emotions, likings, and preferences; they also allow a researcher to access a study participant's attitude, intelligence, personality characteristics, emotions, behavioral tendencies, among many other possible dimensions of psychological constructs.

Many modern human behavior labs employ biometric measures instead of self-reporting, since they believe that they provide more unbiased and objective data. However, when combined with physiological recordings, psychological scales can help a researcher gain deeper insights into underlying factors driving human cognition and behavior.

Self-report scales can be selected based on what information they can retrieve, and how this information is relevant to a given study of social and/or cognitive behavior. Even though these are individual measures and can only provide scores of individual trait and state characteristics, differences in interactions and emotional regulation during the conversation task are partly influenced by participants' intrinsic differences.

Psychological scales are supposed to be validated by either comparing its results to the results of another well-known scale or by contrasting its results to hard evidence that support its findings. For this reason, a researcher should be very careful before modifying an existing scale by deleting or altering questions, as this can affect the results.

Another factor to consider is how much time your participant is willing to volunteer for your study. Some scales have very high correlation among each other, so depending on the construct you are investigating, you can select these strategically; that is, if two scales correlate very highly and measure similar constructs, for the sake of decreasing the amount of time a participant would need to fill out all required surveys, you can select one out of the two.

A researcher may decide to create their own scale or to use an existing one. The advantage of using a scale that has already been used, validated, and published is that—besides the fact that it already might have a scoring rubric with instructions on how to interpret the results—results obtained in one study can be compared to other similar studies in the literature, making the results obtained a little more generalizable. There is a large number of already created, validated, and published scales. Researchers should start by looking through the American Psychological Association database. It offers a comprehensive and searchable collection of surveys called PsycTESTS. It lists over 50,000 scales in more than 40 languages, along with validation instruments and reliability information, and test types in a variety of subject areas. Most of the scales are available in downloadable PDF format. PsycTESTS comprises an extensive collection of items associated with psychological measures, scales, surveys, and other instruments essential to the research needs of professionals, students, and educators across the behavioral and social sciences. In this repository, it is easy to search through thousands of research instruments and their psychometric properties.

Chapter 2

Electrocardiography

A BRIEF OVERVIEW OF ELECTROCARDIOGRAPHY

An electrocardiogram (ECG or EKG) is a record or display of a person's heartbeat produced by electrocardiography. It involves the process of recording the electrical activity of the heart over a period of time using electrodes placed on the skin of an individual's chest, arms, or legs. These electrodes register the subtle electrical voltage changes on the skin that arise from the heart muscle's electrophysiologic pattern of depolarizing and repolarizing during each heartbeat. The signal output can then be interpreted as heart rate (units: beats per minute [bpm]).

Heart rate provides an excellent window into autonomic function associated with arousal and emotional processing, and due to its ease of use and simple application, it has been widely used in human behavior research. An individual's heart rate, both at rest and during exercise, can reveal their heart health and their aerobic capacity. In general, monitoring heart rate is a way to keep track of exercise intensity; as exercise intensity increases, the heart rate also increases.

Healthy biological systems exhibit complex patterns of variability that can be described by mathematical chaos. This means that a healthy heart is not a precise metronome. The oscillations of a healthy heart are complex and nonlinear, and therefore, constantly changing, which allows the cardiovascular system to rapidly adjust to sudden physical and psychological challenges and quickly return to homeostasis (i.e., a resting rate).

Resting Heart Rate

When at rest, the heart is pumping the lowest amount of blood to supply the oxygen the body needs. A normal resting heart rate for an adult ranges from 60 to 100 beats a minute. Generally, a lower heart rate at rest implies more efficient heart function and better cardiovascular fitness. For example, a well-trained athlete might have a normal resting heart rate between 40 and 60 beats a minute. However, many factors can influence heart rate, including air temperature, activity level, fitness level, emotions, body size, body position, emotions, and medications.

Maximum Heart Rate

The rate at which the heart is beating when it is working its hardest to meet the body's oxygen needs is its maximum heart rate. The maximum heart rate plays a major role in setting aerobic capacity, that is, the amount of oxygen one is able to consume. For example, several observational studies have demonstrated that men and women with mild cognitive impairment who raised their aerobic capacity also improved their performance on tests of memory and reasoning.

The Heartbeat

The generation of a heart beat involves the sinoatrial node, which is known to function as the pacemaker of the heart. The sinoatrial node generates action potentials that travel throughout the cardiac tissue, causing regions of the heart muscle to contract, forming a heartbeat.

The parasympathetic and the sympathetic nervous systems—the two branches of the autonomic nervous system—operate antagonistically to regulate the lengths of time between consecutive heartbeats. Although both autonomic branches exert a constant influence on heart rate, parasympathetic influence is predominant at rest (Berntson et al., 1997).

Sympathetic activation has an excitatory influence on the firing rate of the sinoatrial node and, among other things, results in increased heart rate. By contrast, parasympathetic activation has an inhibitory influence on the pace-making activity of the sinoatrial node and produces decreased heart rate. Therefore, the interval between heartbeats is constantly increasing and decreasing. The time between heartbeats is measured in milliseconds (ms) and is called an interbeat interval (IBI) or an RR interval (see figure 2.1).

The sympathetic and parasympathetic nervous systems rely on different signaling mechanisms with different temporal effects. The sympathetic influence on heart rate is mediated by the neurotransmission of norepinephrine and possesses a slow course of action on cardiac function (Appelhans

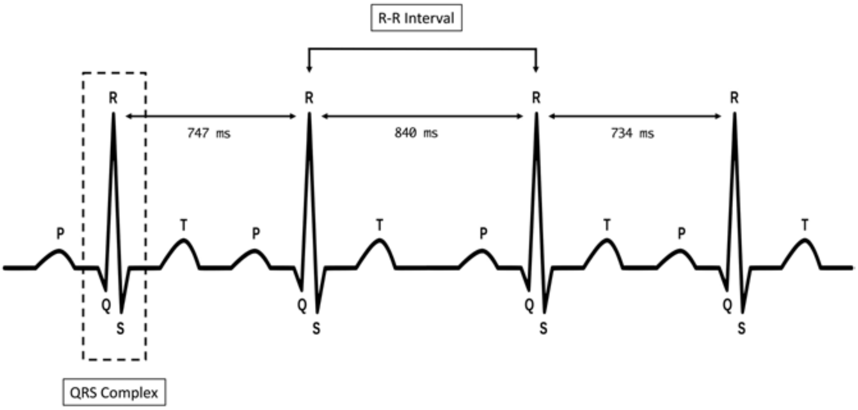

Figure 2.1 The QRS Complex. This Image Illustrates Four Heartbeats along with the Measurement of the Interval between the Heartbeats, or Interbeat Intervals, Measured in Milliseconds. The image also shows the RR interval, which is the interval between two subsequent R-peaks. *Source:* Diagram created by author.

& Luecken, 2006). By contrast, parasympathetic regulation of the heart is mediated by acetylcholine neurotransmission and has a very short latency of response (Pumprla, Howorka, Groves, Chester, & Nolan, 2002). The ability of the parasympathetic nervous system to rapidly modulate cardiac activity determines the flexibility in responding to environmental demands with physiological and emotional arousal.

The QRS Complex

The QRS complex is a name for the combination of three of the graphical deflections seen on a typical ECG. It is usually the central and most visually obvious part of the tracing (see figure 2.1). It corresponds to the depolarization of the right and left ventricles of the human heart. In a continuous ECG recording, each QRS complex is detected, and the RR intervals (i.e., all intervals between two adjacent R-peaks) are determined, which produces the reading of the heart rate.

Heart Rate Variability

While the heart rate is the number of heartbeats per minute, heart rate variability (HRV) is the fluctuation in the time intervals between adjacent heartbeats, hence the term *variability* (see figure 2.1). HRV indexes neurocardiac function and is generated by heart-brain interactions and dynamic nonlinear autonomic nervous system processes. HRV reflects the degree to which cardiac activity can be modulated to meet changing situational demands.

HRV is a noninvasive tool that allows the examination of cardiovascular autonomic function through the measurement of variations in RR intervals (see figure 2.1). HRV was first employed in clinical settings before it was applied to sport science contexts and studies of social behaviors and cognitive performance. The use and analysis of HRV has become increasingly common because it is simple, noninvasive, and sensitive to physiological and psychological changes (Thayer et al., 2012).

The Central Autonomic Network

The autonomic influences on heart rate are regulated remotely by the distributed network of brain areas composing the central autonomic network (Benarroch, 1993). The central autonomic network (CAN) supports regulated emotional responding by flexibly adjusting physiological arousal in accordance with changing situational demands. Thus, the CAN is critically involved in integrating physiological responses in the services of emotional expression, responding to environmental demands, goal-directed behavior, and homeostatic regulation. The neuroanatomical composition of the CAN includes cortical (medial prefrontal and insular cortices), limbic (anterior cingulate cortex, hypothalamus, central nucleus of the amygdala, bed nucleus of the stria terminalis), and brainstem (periaquaductal gray matter, ventrolateral medulla, parabrachial nucleus, nucleus of the solitary tract) regions. The CAN receives input from visceral afferents regarding the physiological conditions inside the body and input from sensory processing areas in the brain regarding the external sensory environment (Appelhans & Luecken, 2006). This input allows the CAN to dynamically adjust physiological arousal, including arousal associated with emotional expression and regulation, in response to changes in internal and external conditions. The output of the CAN is transmitted to the sinoatrial node (and many other organs) through the sympathetic and the parasympathetic nervous systems and directly influences heart rate. Therefore, HRV reflects the moment-to-moment output of the CAN and, by proxy, an individual's capacity to generate regulated physiological responses in the context of emotional expression (Thayer & Siegle, 2002).

Respiratory Sinus Arrhythmia

Breathing air into the lungs temporarily halts the parasympathetic influence on heart rate, producing an increase in heart rate. Breathing air out of the lungs reinstates parasympathetic influence on heart rate, resulting in a heart rate decrease. This rhythmic oscillation in heart rate produced by breathing is called *respiratory sinus arrhythmia.* As only cardiac parasympathetic activity possesses a latency of action rapid enough to covary with respiration, respiratory sinus arrhythmia is a phenomenon known to be entirely mediated by the parasympathetic nervous system. In fact, a large majority of parasympathetically mediated variation in heart rate is produced by respiratory sinus arrhythmia, and many researchers have reported the magnitude of respiratory sinus arrhythmia as an index of parasympathetically mediated HRV (Appelhans & Luecken, 2006).

Autonomic Flexibility

HRV is a very sensitive index of the health of the body's stress response systems, and it is one way to measure a person's autonomic flexibility. To illustrate what autonomic flexibility is, imagine a fit runner; while this person is running, their heart rate will go up, and when they stop, their heart rate will go down; if they are in very good shape, their heart rate will go down very quickly. In other words, the heart is able to respond quickly to get a person out of a stressful situation, but after that situation has passed and the body needs to get back to its normal functions, it should respond quickly and flexibly. People with lower HRV have an inflexible response, which could mean that something is wrong with their autonomic function. This is observed in cases of depression and post-traumatic stress disorder, for example. A low HRV (or less variability between the heart beats) typically indicates that the body is under constant stress, which could be caused by exercise, psychological events, or other internal or external stressors.

Research has shown that the ability of the parasympathetic nervous system to rapidly modulate cardiac activity determines a person's flexibility in responding to environmental demands. Two major theories relate the autonomic flexibility represented by HRV with regulated emotional responding. One of them is the polyvagal theory (Porges, 1997), which posits that the vagal complex has afferent fibers terminating in the nuclei of the facial and trigeminal nerves and includes portions of cranial nerves that mediate facial expression, head turning, vocalization, listening, and other socially relevant behaviors. The connection of the ventral vagal complex and these cranial nerves provides a mechanism by which cardiac states can be coordinated with social behaviors (Porges, 2001). The polyvagal theory states that the ability of the ventral vagal complex to rapidly withdraw its inhibitory influence allows humans to rapidly engage and disengage with their environment without the metabolic cost of activating the slower responding SNS. The polyvagal theory emphasizes the relation of respiratory sinus arrhythmia, which indexes parasympathetically mediated autonomic activity and the regulation of the emotional processes that underlie social behavior.

Another theoretical approach that links HRV to autonomic flexibility is Thayer and Lane's (2000) Model of Neurovisceral Integration, which relates emotional responding with HRV. This model posits that behavioral, cognitive, and physiological processes involved in emotion are subsystems of a larger, self-organizing system. Specific emotional states emerge from interactions among these lower-level elements along the lines of certain control parameters. In support of the Model of Neurovisceral Integration, Thayer and Lane (2000) cite several studies that suggest that the dimensions of valence and arousal represent the control parameters that guide the organization of emotional responses. This model views the CAN as the neurophysiological command center governing cognitive, behavioral, and physiological elements into regulated emotional states. The CAN does this by inhibiting other potential responses which require reciprocal communication among system components (e.g., feedback loops), sensitivity to the initial conditions of the system, and the existence of multiple pathways to a response (e.g., combinations of sympathetic and parasympathetic activity), all elements of a neuroviscerally integrated dynamic system. Such inhibition procedure is thought to be mediated synaptically in the brain and vagally in peripheral system (Thayer & Friedman, 2002). From this perspective, HRV can be considered a proxy for the CAN's ability to regulate the timing and magnitude of an emotional response through inhibition, taking into account contextual factors.

These two theories are similar in that they specify a critical role for parasympathetically mediated inhibition of autonomic arousal in emotional expression and regulation, and maintain that HRV measures are informative about individuals' capacity for this aspect of regulated emotional responding. However, these theories differ in a few of their premises. For example, the Model of Neurovisceral Integration is premised on neuroanatomical links between the autonomic nervous system and brain regions associated with emotional processing (e.g., cortical and limbic areas of the CAN), whereas the polyvagal theory largely rests on the neural connections between the vagus nerve and other cranial nerves that control the peripheral structures that are involved in the behavioral expression of emotion (e.g., the muscles of the face and head). Attending to different neuroanatomical substrates has led to divergent extensions of each theory. Nevertheless, integrating the neuroanatomical components from both models should help researchers generate more intricate hypotheses about the interaction of autonomic, cognitive, and behavioral aspects of emotional expression and regulation.

Emotional Regulation

Vagal tone is frequently used to assess heart function, emotional, and attentional regulation. Vagal tone specifically refers to the continual nature of baseline parasympathetic action. While baseline vagal input is constant, the degree of stimulation it exerts is regulated by a balance of inputs from sympathetic and parasympathetic branches of the autonomic nervous system, with parasympathetic activity generally being dominant.

Low vagal tone has been correlated with poor affect regulation and inhibition. Porges (1993) showed that low vagal tone is associated with poor affect regulation, decreased responsivity to stimuli, and increased vulnerability to stress in infancy and childhood. Kagan et al. (1988) showed that there was a greater shift toward low-frequency power in HRV under cognitive stress in behaviorally inhibited children. There were other important physiological differences between inhibited and uninhibited children that correlated with decrease HRV. The authors found differences in salivary cortisol and norepinephrine levels (these are “stress” hormones) and pupillary size at both baseline and in response to cognitive stress. These findings suggest that heightened sympathetic activity with involvement of neural circuits in the limbic system might be the basis for behavioral inhibition. Others have noted an excessive vagal reactivity to various environmental challenges among children who are temperamentally shy and angrily reactive.

On the other hand, higher vagal tone is positively correlated with children’s social engagement, with teacher reports of social competence and expression of empathy toward others in distress. Higher vagal tone also appears to protect children who are exposed to marital discord and hostility from developing behavioral problems (Katz & Gottman, 1995).

Therefore, the development of appropriate social behavior is dependent on the body’s ability to regulate vagal tone, and vagal tone mirrors a person’s response and adaptivity to environmental challenges and demands, based on the observation that vagally mediated component of HRV reflects adaptivity (or maladaptivity) to environmental challenges and indexes ability (or inability) to modulate affect responses.

The Use of HRV in Research

Recent decades have seen increasing use of HRV as a noninvasive marker of cardiac autonomic function and of central processes involved in autonomic function regulation. Developmental research has linked cardiac vagal tone to an individual’s responsivity to environmental challenges and a decrease in vagal component of HRV may reflect deficiencies in emotional regulatory system. Studies with children and adolescents suggest that a less effective cardiac vagal function is seen in various pathophysiological conditions characterized by emotional dysregulation. Thus, alteration in cardiac vagal modulation may be the common mechanism underpinning the association between negative affective states and emotional dysregulation. Therefore, HRV represents one of the most promising autonomic activity markers.

HRV has become the conventionally accepted term to describe variations of both instantaneous heart rate and interbeat intervals (RR). HRV frequency-domain analyses contributed to the understanding of the autonomic background of RR interval fluctuations in the heart rate record. With the availability of new, digital, high-frequency, 24-hour multichannel electrocardiographic recorders, HRV has the potential to provide additional valuable insight into physiological and psychological conditions.

ELECTROCARDIOGRAPHY AND LANGUAGE RESEARCH

Electrocardiography is the recording of a person's heart rate, and the measurement of the variation of the IBIs over time provides a person's HRV. An important component of learning a second language relies on components of social connection and social behavior and on a learner's ability to cope with anxiety or overcome the fear to take chances and make mistakes in the process. A large portion of the research on HRV has shown that there are strong correlations between HRV and social behavior. HRV has proven to be a reliable biomarker of a person's social predisposition and ability to regulate emotions efficiently, making it a powerful resource for second language researchers.

HRV has been shown to serve as a reliable index of a person's capacity to regulate and express their own emotions. Research has shown that reduced HRV correlates with social anxiety disorder and symptom severity. The fact that low HRV has been shown to correlate with social stress and social anxiety reinforces the usefulness of this physiological parameter for empirical investigations of second language learning theories. Foreign language anxiety, classroom anxiety, test anxiety, and the effect of external stressors on students' overall performance in language learning have one thing in common, which is the fact that they are manifestations of anxiety dysregulation, and they are all highly relevant to SLA research.

For example, a study conducted by Miller, Xia, and Hastings (2019) assessed the relationship between resting HRV and neural activation when participants' observe and imitate emotional faces. This is a behavior that language learners have to rely on in order to interpret gaps in communication. Miller, Xia, and Hastings (2019) focused on brain regions implicated in sensorimotor resonance, salience detection, and arousal. They used ECG data to compute participants' resting HRV. They found that resting HRV measures were negatively correlated with activation in a portion of the inferior frontal gyrus showing mirror neuron properties, the insula and the amygdala in response to observation, but not imitation, of emotional faces. Thus, they concluded that resting HRV was linked to a person's sensitivity to others' emotional cues, both in terms of the tendency to map others' emotional facial expressions onto one's own motor system and to rapidly detect and mark others' emotions as salient events. The fact that resting HRV may at least partially reflect a threshold for increased processing of others' facial expressions in search of others' emotional predispositions suggests that it can be a very useful measure of second language learners' ability to cope with linguistic gaps and negotiate for meaning.

In addition, there are a number of other social behaviors that have also been shown to correlate with resting HRV and that are relevant to applied linguistics research. Resting HRV has been shown to be positively correlated with self-reported empathy (Lischke et al., 2018) and with positive affective response to positive interactions (Diamond, Hicks, & Otter-Henderson, 2011). In addition, higher resting HRV has been shown to predict greater social engagement and reported positive emotion in response to social activities (Isgett et al., 2017), as well as more cooperative behavior (Beffara, Bret, Vermeulen, & Mermillod, 2016). Resting HRV is also positively associated with social support seeking, perceptions of social acceptance, and social integration (Geisler, Kubiak, Siewert, & Weber, 2013). This suggests that resting HRV might explain why some learners have a strong preference for group work and group-based classroom activities while others prefer to work alone. Physiological predispositions that promote and regulate social behaviors are extremely important for second language learning, as it encourages language learners to seek out opportunities to practice the language, making this a rich area to explore in SLA research.

IMPORTANT CONSIDERATIONS ABOUT METHODOLOGICAL PROCEDURES

Factors that Influence HRV

Awareness of the *context* of recording and *subject* variables can aid interpretation of both 24-hour and short-term HRV measurements. Important contextual factors include recording period length, detection or recording method, sampling frequency, and respiration. Important subject variables are age, sex, heart rate, and health status like level of physical activity, fitness, and sleep-wake cycle. Other subject factors that can affect HRV are reflexes of baroreceptors, chemoreceptors, and cardiopulmonary receptors; the renin-angiotensin system (a hormone system that regulates blood pressure and fluid balance); physical or mental stress; cardiovascular and non-cardiovascular diseases; medications such as beta-blockers, atropine, glycosides, anesthetics, and so on; influences of posture and position; movement; recency of physical activity, tasks, demand characteristics, and relationship variables, all of which can affect measurements subtly or even greatly by changing autonomic nervous system activation, breathing mechanics, and emotions.

Recording Period Length

The length of the recording period significantly affects both HRV time-domain and frequency-domain measurements. Since longer recordings are associated with increased HRV, it is inappropriate to compare metrics like SDNN when they are calculated from periods of different length. For example, resting values obtained from short-term monitoring periods correlate poorly with 24-hour indices and their physiological meanings may differ.

Detection Methods

There are two common methods of recording heart rate: one is the traditional electrocardiography (ECG) and the other one is a newer method called photoplethysmography (PPG). ECGs measure the electrical activity of the heartbeat. With each beat, an electrical impulse travels through the heart. This electrical wave causes the muscle to squeeze and pump blood from the heart. A normal heartbeat on ECG will show the timing of the top and lower chambers. The right and left atria or upper chambers make the first wave called a "P wave," following a flat line when the electrical impulse goes to the bottom chambers. The right and left bottom chambers or ventricles make the next wave called a "QRS complex." The final wave or "T wave" represents electrical recovery or return to a resting state for the ventricles.

A PPG is a simple optical technique used to detect volumetric changes in blood in peripheral circulation. It is a low-cost and noninvasive method present in most fitness wearable devices that make measurements at the surface of the skin. PPG makes uses of low-intensity infrared light. When light travels through biological tissues it is absorbed by bones, skin pigments, and both venous and arterial blood. Since light is more strongly absorbed by blood than the surrounding tissues, the changes in blood flow can be detected by PPG sensors as changes in the intensity of light. The voltage signal from PPG is proportional to the quantity of blood flowing through the blood vessels. Even small changes in blood volume can be detected using this method, though it cannot be used to quantify the amount of blood. A PPG signal has several components including volumetric changes in arterial blood which is associated with cardiac activity, variations in venous blood volume which modulates the PPG signal, a DC component showing the tissues' optical property and subtle energy changes in the body. Some major factors affecting the recordings from the PPG, thus creating artifacts on the recorded data, are site of measurement and the contact force between the site and the sensor.

The reliability and usefulness of PPG devices in physiological research are being explored as these wearable devices also provide other physiological information besides heart rate, such as blood pressure, respiration rate, electrodermal activity, temperature, among others. In comparative studies, ECGs and PPGs yielded discrepancies of less than 6 percent for most HRV measures, but about 30 percent discrepancies were found for HRV parameter pNN50 in a study conducted by Jeyhani et al. (2015). For the moment, ECG devices are still the golden standard for being more reliable and more widely used by physiologists.

Sampling Frequency

While a minimum sampling frequency of 500 Hz may be required to detect the R-spike fiducial point of the ECG when RSA amplitude is low, a sampling rate of 125 Hz (93) or 200 Hz may be sufficient when RSA amplitude is normal. Very low RR interval variability requires higher sampling rates for adequate temporal resolution. Lower sampling rates may threaten the validity of HRV frequency-domain and nonlinear indices.

Respiration

Greater tidal volumes and lower respiration rates increase RSA; increasing respiration depth raised HR Max-HR Min and did not reduce time-domain, frequency-domain, or nonlinear HRV measures. Increasing or decreasing respiration rate from a client's resonance frequency—the breathing rate that best stimulates the cardiovascular system—may lower short-term time-domain measurements and LF band power, while raising or lowering HF power, respectively (Shaffer, McCraty, & Zerr, 2014).

Age

HRV time-domain measurements decline with age. For example, Bonnemeier et al. (2003) obtained 24-hour recordings from 166 healthy volunteers (85 men and 81 women) aged 20–70. They found that the most dramatic HRV parameter decreased between the second and third decades of a person's life. Almeida-Santos et al. (2015) obtained 24-hour ECG recordings of 1,743 subjects 40 to 100 years of age. They found a linear decline in SDNN, SDANN, and SDNN index. However, they discovered a U-shaped pattern for RMSSD and pNN50 with aging, decreasing from 40 to 60 and then increasing after age 70.

Sex

A meta-analysis of 296,247 healthy participants examined 50 HRV measures (Koenig & Thayer, 2016). Women had higher mean heart rate (HR; smaller RR intervals) and lower SDNN and SDNN index values, especially in 24-hour studies, compared to men. They showed lower total, VLF, and LF power, but greater HF power. While women showed relative vagal dominance, despite higher mean HR, men showed relative SNS dominance, despite their lower HR.

Health

Time-domain measurements rise with increased aerobic fitness and decline with decreased health (Agelink, Boz, Ulrich, & Andrich, 2002). Autonomic cardiac dysregulation is a critical process that underlies the manifestation and perpetuation of symptoms broad spectrum symptoms of poor health. HRV has been shown to be useful in predicting morbidities from common mental (e.g., stress, depression, anxiety, PTSD) and physical disorders (e.g., inflammation, chronic pain, diabetes, concussion, asthma, insomnia, fatigue), all of which increase sympathetic output and create a self-perpetuating cycle that produces autonomic imbalance.

Analysis of HRV

HR is the number of heartbeats per minute. Faster HRs reduce the time between successive beats (interbeat intervals [IBI]) and the opportunity for the IBIs to vary, which lowers HRV. Conversely, slower HRs increase the time between adjacent heartbeats and the chance for IBIs to vary, which raises HRV. This phenomenon is called *cycle length dependence*. The interbeat interval (IBI or RR) variations present during resting conditions represent a fine tuning of the beat-to-beat control mechanisms. Vagal afferent stimulation leads to reflex excitation of vagal efferent activity and inhibition of sympathetic efferent activity. The opposite reflex effects are mediated by the stimulation of sympathetic afferent activity. Efferent vagal activity also appears to be under "tonic" restraint by cardiac afferent sympathetic activity. Efferent sympathetic and vagal activities directed to the sinus node are characterized by discharge largely synchronous with each cardiac cycle, which can be modulated by central (e.g., vasomotor and respiratory centers) and peripheral (e.g., oscillation in arterial pressure and respiratory movements) oscillators. These oscillators generate rhythmic fluctuations in efferent neural discharge which manifest as short- and long-term oscillation in the heart period. There are three main approaches to the analysis of HRV: *time-domain*, *frequency-domain*, and *nonlinear*. They are outlined in the sections that follow (see tables 2.1, 2.2, and 2.3).

Table 2.1 ***HRV Time-Domain Parameters***

Parameter	*Description*
RR	Interval between two heartbeats (R spikes in the QRS complex/ ECG)
SDRR	Standard deviation of RR intervals
NN	Interval between two heartbeats (emphasis on "normal" heartbeats)
SDNN	The standard deviation of all NN intervals. The SDNN describes a median of the variability. It consists of parts from sympathetic and parasympathetic nervous system. The SDNN can be described as an overall variability or total power. You can describe it to the patient as the total power of the regulation system
SDANN	The standard deviation of the average of the NN interval for all 5-minute periods of a 24-hour recording. Higher values indicate increased parasympathetic activity
SDANN-i	The standard deviation of the average normal NN interval for all 5-minute periods of a 24-hour recording. Higher values indicate increased parasympathetic activity
RMSSD	The square root of the root mean square of the sum of all differences between successive NN intervals. It correlates to high-frequency components. Higher values indicate increased parasympathetic activity.
SI	Stress index, reflects sympathetic activity
NN50	The number of pairs of successive NN intervals that differ by more than 50 milliseconds in the entire recording. Higher values indicate increased parasympathetic activity
pNN50	The percentage of successive intervals that differ by more than 50 milliseconds. Higher values indicate increased parasympathetic activity
SDSD	The standard deviation of the differences between successive NN intervals
NNx	Number of valid adjacent NN values not separated by data breaks
pNNx	Proportion of valid adjacent NN values not separated by data breaks
Cycles	Number of available NN values
HR Max– HR Min	Average difference between the highest and lowest heart rates during each respiratory cycle (unit: bpm)
HTI	HTI stands for HRV Triangular Index. This is the integral of the density of the RR interval histogram divided by its height

Source: Table created by author.

Time-Domain Measurements of HRV

Variations in heart rate may be evaluated by a number of methods. Perhaps the simplest to perform are the time-domain measures. Time-domain analysis is most commonly used in clinical applications of HRV. It is also less sensitive to noise and signal artifacts than the frequency-domain methods. Time-domain analysis uses instantaneous heart rate or IBIs (see table 2.1).

Table 2.2 ***HRV Frequency-domain Parameters***

Frequency Band	*Frequency Range*	*Description*
ULF	≤0.003 Hz	The ultra-low-frequency (ULF) band requires a recording period of at least 24 hours, and it is highly correlated with the SDANN time-domain index.
VLF	0.0033–0.04 Hz	The-very-low frequency (VLF) band requires a recording period of at least 5 minutes, but may be best monitored over 24 hours. Within a 5-minute sample, there are about 0–12 complete periods of oscillation. Very-low-frequency power is strongly correlated with the SDNNI time-domain measure.
LF	0.04–0.15 Hz	The low-frequency (LF) band is typically recorded over a minimum 2-minute period. LF power may be produced by both the parasympathetic and the sympathetic nervous systems. In resting conditions, the LF band reflects baroreflex activity and not cardiac sympathetic innervation.
HF	0.15–0.4 Hz	The high-frequency (HF) band is conventionally recorded over a minimum 1-minute period. The HF band reflects parasympathetic activity and is called the *respiratory* band because it corresponds to the HR variations related to the respiratory cycle. These phasic HR changes are known as respiratory sinus arrhythmia and may not be a pure index of cardiac vagal control.
LnHF	-	A natural logarithm (Ln) is the logarithm to the base of a numeric value. LnHF, under controlled conditions and while breathing at a normal rate, can be used to estimate vagal tone.
LF/HF Ratio	-	The ratio of LF to HF power (LF/HF ratio) was originally based on 24-hour recordings, during which both PNS and SNS activity contribute to LF power, and PNS activity primarily contributes to HF power. The intent was to estimate the ratio between SNS and PNS activity. In this model, a low LF/HF ratio reflects parasympathetic dominance. By contrast, a high LF/HF ratio indicates sympathetic dominance. However, this assumption is controversial and interpretation of LF/HF ratios depends on specific measurement conditions.

Source: Table created by author.

In most analyses of the HRV, the most frequently used time-domain parameters are RMSSD (a parameter of the parasympathetic nervous system), SI (a parameter of the sympathetic nervous system), and SDNN (standard deviation) (for more information, see Shaffer & Ginsberg, 2017).

Time-domain indices quantify the amount of HRV observed during monitoring periods that may range from approximately 2 minutes to 24

Table 2.3 ***HRV Nonlinear Parameters***

Parameter	*Description*
S	Area of the ellipse which represents total HRV
SD1	Poincaré plot standard deviation perpendicular the line of identity
SD2	Poincaré plot standard deviation along the line of identity
SD1/SD2	Ratio of SD1-to-SD2
ApEn	Approximate entropy measures the regularity and complexity of a time series. ApEn was designed for brief time series in which some noise may be present and makes no assumptions regarding underlying system dynamics. Applied to HRV data, large ApEn values indicate low predictability of fluctuations in successive RR intervals. Small ApEn values mean that the signal is regular and predictable.
SampEn	Sample entropy measures the regularity and complexity of a time series. It was designed to provide a less biased and more reliable measure of signal regularity and complexity. SampEn values are interpreted and used like ApEn.
DFA α1	Detrended fluctuation analysis extracts the correlations between successive RR intervals over different time scales, and DFA α1 describes short-term fluctuations.
DFA α2	Detrended fluctuation analysis extracts the correlations between successive RR intervals over different time scales, and DFA α2 describes long-term fluctuations.
D2	Correlation dimension, which estimates the minimum number of variables required to construct a model of system dynamics. DFA is designed to analyze a time series that spans several hours of data.

Source: Table created by author.

hours. From a series of instantaneous heart rates or cycle intervals, particularly those recorded over longer periods, traditionally 24 hours, more complex statistical time-domain measures can be calculated. These may be divided into two classes: (a) those derived from direct measurements of the NN intervals or instantaneous heart rate and (b) those derived from the differences between NN intervals. These variables may be derived from analysis of the total electrocardiographic recording or may be calculated using smaller segments of the recording period. The latter method allows comparison of HRV to be made during varying activities, for example, rest, sleep, and so on.

Frequency-Domain Measurements of HRV

Using Fast Fourier Transformation or autoregressive modeling, it is possible to separate HRV into its components ULF, VLF, LF, and HF rhythms, each of which operates within different frequency ranges, analogous to a prism that refracts light into its component wavelengths. Below are the main frequency-domain measures of HRV (see table 2.2).

Nonlinear Measurements of HRV

Life is aperiodic (i.e., oscillations occur without a fixed period) and operates between randomness and periodicity. Nonlinearity means that a relationship between variables cannot be plotted as a straight line. Twenty-four-hour ECG monitoring yields a time series of RR intervals, and nonlinear measurements index the unpredictability of a time series, which results from the complexity of the mechanisms that regulate HRV. Nonlinear indices correlate with specific frequency- and time-domain measurements when they are generated by the same processes. A poincaré plot is a popular nonlinear measurement in HRV analysis that is used both with short-term (5 to 30 min) and long-term (24 h) analyses. It is graphed by plotting every R-R interval against the prior interval, creating a scatter plot, commonly used to assess the dynamics of the HRV signal, and describe the sympathetic and parasympathetic modulation of heart rate (Brennan, Palaniswami, & Kamen, 2002). Poincaré plot analysis also allows researchers to visually search for patterns buried within a time series (a sequence of values from successive measurements). A poincaré plot is also a quantitative technique in the sense that it has various parameters, such as the short-term variability (SD1) and the long-term variability (SD2) to quantify the information from the plot. This section reviews S, SD1, SD2, SD1/SD2, approximate entropy (ApEn), sample entropy (SampEn), detrended fluctuation analysis (DFA) α1 and DFA α2, and D2 nonlinear measures (see table 2.3).

In sum, the selection of HRV time-domain, frequency-domain, and nonlinear metrics to assess progress in clinical and optimal performance interventions can be guided by peer-reviewed studies and supplemented by values from specialized populations. Researchers measure HRV using time-domain, frequency-domain, and nonlinear indices. Time-domain values measure how much HRV was observed during the monitoring period. Recording period length strongly influences time-domain values. Shorter epochs are associated with smaller values and poorly estimate 24-hour values. Frequency-domain values calculate absolute or relative signal power within the ULF, VLF, LF, and HF bands. Recording period length limits HRV frequency-band measurement. Minimum recommended periods include ULF (24 h), VLF (5 min, 24 h preferred), LF (2 min), and HF (1 min). Nonlinear indices measure the unpredictability and complexity of a series of IBIs. The relationship between nonlinear measurements and autonomic flexibility is complex.

Standard Recording Devices

Devices to monitor and record heart rate that have been widely referred to in the literature and that have been properly validated by comparing results to properly recorded lead wired ambulatory standards are the Polar (Polar OY, Finland) heart rate monitors—Polar S810 (Gamelin, Baquet, & Berthoin, 2008), RS800 (Quintana, Heathers, & Kemp, 2012), Polar V800 (Giles, 2016), and the Biopac ECG 100C (Biopac Systems, Inc.) (Judson et al., 2009). Polar files can be downloaded to a computer using their extraction software FlowSync, as CSV files; then, after being examined for artifacts, they can be imported into Kubios for analysis. On the other hand, Biopac's recorders can be paired with their own Data Acquisition (DAQ) systems, namely MP160 and MP36R. A DAQ is a means to process the recording or an electrical or physical phenomenon such as voltage, current, temperature, pressure, or sound with a computer, and it consists of sensors, a DAQ measurement hardware, and a computer with programmable software. Biopac's equipment comes with its native software *AcqKnowldge*, through which the researcher can easily visualize, manipulate, and process data, real-time or after the experiment is over.

Recommendations for Data Collection

Any protocol for heart rate data collection that will look at HRV parameters needs to take into account the following steps for the preparation of equipment and participants.

Before the Experiment

Participants should be asked to abstain from caffeine-containing food and drinks prior to the test and to only consume a light meal 2 hours prior to testing. Participants should be allowed to rest before the experiments starts. Experiments should take place at around the same time of day if several days will be required to collect data.

Preparing the Participant for the Experiment

If the researcher is using ambulatory lead electrodes, the participant's skin must be clean (shaved if necessary) and prepared for the attachment of the ECG electrodes. The electrodes must be placed in a proper configuration (see figure 2.2).

If the researcher is using Polar hear rate monitors, the study participant will need to wear the heart rate monitor (HRM) strap (e.g., Polar H7). The electrode belt needs to be dampened and placed following Polar's guidelines, tightly but comfortably placed just below the chest muscles.

Resting measurements must be conducted in two positions: sitting down and standing of speaking or reading out loud, in a quiet laboratory, with a comfortable standard temperature of 20.6 ± 1.0 °C.

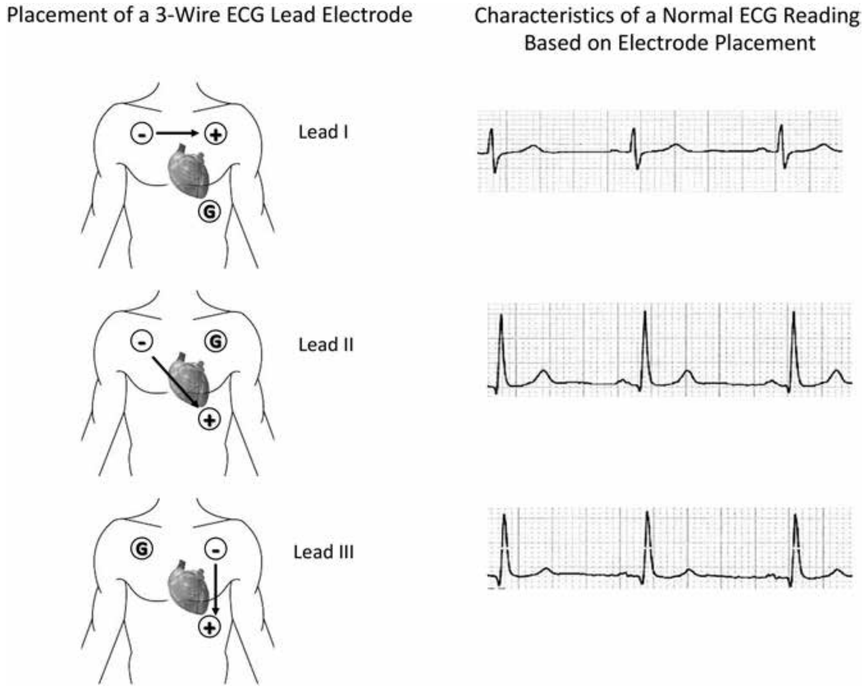

Figure 2.2 Placement of a 3-Wire ECG Lead Electrode. The Three Diagrams Show the Three Possible Placements of a three-Lead ECG Electrode on a Participant's Chest and the Characteristics of a Normal ECG Reading Based on Each Configuration. *Source*: Image created by author.

Recordings of baselines should last around 10 minutes (more than 5 minutes in order to generate VLF values in the HRV data). In order to control for the influences of respiration on HRV (Song & Lehrer, 2003), it is good to ask participants to match their breathing frequency to an auditory metronome set at 0.20 Hz (12 breaths min−1).

Recording during the Experiment

RR interval data can be recorded using either a Polar HRM with a Polar H7 chest strap or a three-lead Biopac ECG 100C (with DAQ MP36/MP160, Biopac Systems Ltd.), at a sampling frequency of 1000 Hz for either device. If using Polar HRMs, R-wave peaks from the ECG data can be detected automatically using a custom peak detection algorithm in Matlab (Mathworks, Cambridge). If using Biopac products, its native software *AcqKnowledge* can perform all waveform recordings and analyses automatically.

The raw ECG traces and detected R waves must be visually assessed to ensure that they are being detected correctly. Ectopic beats must be noted, but not corrected during data collection (wait for post-processing data analysis to correct artifacts). Data is usually saved as RR interval data files, with intervals in milliseconds (ms). The Polar HRM raw unfiltered RR data can be exported as a space delimited.txt file, which can be read by a number of third-party analysis software.

Recommendations for Data Processing

Removal of Artifacts

Before running calculations to obtain HRV from the heart rate data, the researchers must inspect the recorded values. Visual inspection of the raw ECG signal can help detect artifacts (i.e., missed or out of range beats). This is a very important procedure because artifacts can significantly distort both time- and frequency-domain measurements. Artifacts increase power in all frequency bands. Missed beats produce greater increases than extra beats since deviation from a missed beat equals the mean heart period versus half the mean heart period for extra beats. The bias introduced by even a single artifact can easily eclipse the 0.5–1.0 Ln effect sizes typically found in psychophysiological research. When artifacts are present, researchers can select an artifact-free period or manually edit the affected RR intervals.

Checking Data File Length for Periods of Oscillations

When a clean segment is shorter than the recommended length for calculating power within a frequency band, values should be valid as long as it contains at least six full periods of oscillations. For example, estimation of LF power requires at least 2.5 min of clean data (9).

Researchers can replace technical artifacts like missed beats through interpolation based on QRS intervals that precede and follow the contaminated segment. Data analysis software like Kubios can help visualize the raw signal and preserve the original record length and synchrony with other physiological signals (e.g., respiration). The editing of ectopic beats and arrhythmias can be challenging because the resulting changes in stroke volume and cardiac output can affect 10–30 beats instead of the 2 RR intervals that bracket the abnormal heartbeat

Post-processing and Visualization Software: Kubios

The calculation of HRV parameters in segments of NN intervals uses the corrected HRM recordings (i.e., an artifacts-free file). Selected segments of inspected and corrected data can be imported into Kubios HRV (Kubios Oy), a scientifically validated software that allows the calculation of HRV for time-domain, frequency-domain and nonlinear components.

Chapter 3

Blood Pressure

A BRIEF OVERVIEW OF BLOOD PRESSURE

When the heart beats, it pumps blood throughout the body to give it the energy and oxygen it needs. As the blood moves, it pushes against the sides of the blood vessels. The strength of this pushing is what creates "blood pressure." Blood pressure is measured as two separate numbers: systolic blood pressure (SBP) and diastolic blood pressure (DBP). SBP indicates how much pressure the blood is exerting against the artery walls when the heart beats, while DBP indicates how much pressure the blood is exerting against the artery walls while the heart is resting between beats.

In most people, SBP rises steadily with age due to the increasing stiffness of large arteries, long-term build-up of plaque, and an increased incidence of cardiac and vascular disease. Table 3.1 shows the normal range of SBP and DBP values for adults as well as the ranges for low, elevated, and high blood pressure for adults.

A lot of research has been done using blood pressure (BP) as a source of psychophysiological disposition. BP is integrated into the entire cardiovascular system, and a change in BP can be brought about through various centers in the central nervous system and regulated by the heart, blood vessels, and other organs. For example, moods have been shown to correlate with BP. A study conducted by Shapiro et al. (2001) paired diary entries for mood assessment and frequent BP measures to show that moods correlate with changes in BP. The authors then argued that daily experiences of negative mood may be associated with higher BP levels in general.

The relationship between the social network and physical health has been studied extensively, and it has consistently been shown that individuals live

Table 3.1 ***Blood Pressure Levels for Adults***

Blood Pressure (BP) Category	*Systolic mmHg (upper number)*		*Diastolic mmHg (lower number)*
Low	Less than 90		Less than 60
Normal	90–120	and	60–80
Elevated	120–130	and	Less than 80
High BP (Hypertension) Stage 1	130–140	or	80–90
High BP (Hypertension) Stage 2	140 or higher	or	90 or higher
High BP (Hypertension) Stage 3	Higher than 180	and/or	Higher than 120

Notes: These ranges are suggested by the American Heart Association.
Source: Table created by author.

longer, have fewer physical symptoms of illness, and have lower BP when they are a member of a social network as opposed to when they are isolated. Much of the research has focused on the benefits of receiving social support from the network and the effects of giving to others within the network have been neglected.

BP AND LANGUAGE RESEARCH

One example of an area of second language research that lends itself well to the use of BP measurement is the investigation of responses to potential threats to one's identity. SLA literature has extensively treated identity as a central issue that relates to successful second language learning. Identity is an important construct in language research, and it is defined as "how a person understands his or her relationship to the world, how that relationship is structured across time and space, and how the person understands possibilities for the future" (Norton, 2013, p. 45). Contemporary models of stigma propose that contexts that trigger concerns about confirming negative stereotypes or being a target of prejudice are threatening to people's sense of self-integrity and identity (Major, Eliezer, & Rieck, 2012). Social identity threat is the psychological state that occurs in situations where people feel at risk of being devalued because of their social identity, or fear being judged through the lens of negative stereotypes (Steele, Spencer, & Aronson, 2002). Identity-threatening situations are assumed to be stressful, triggering involuntary physiological, cognitive, emotional, and behavioral reactions. To cope with these stress reactions and successfully negotiate threatening interactions, stigmatized individuals engage in self-regulatory efforts, such as trying to suppress negative cognitions and emotions (Johns, Inzlicht, & Schmader, 2008) or engaging in behaviors to overcome negative stereotypes (Shelton, Richeson, & Salvatore, 2005).

These coping efforts are costly. Situational cues that make concerns about identity threat salient lead to increased stress among stigmatized individuals, as indexed by psychological and cardiovascular responses. BP reactivity is a commonly used measure of stress that has been reliably and prospectively linked to prolonged negative emotions. For example, research has shown that when a person engages in a negative experience that requires self-regulation or control after or during the experience, their executive attentional capacity is temporarily depleted, leading to impaired performance on subsequent tasks that require executive control (Muraven & Baumeister, 2000). Contending with identity-threatening situations has been shown to increase BP, deplete executive attentional capacity, and impair performance on subsequent tasks requiring executive control (Inzlicht & Kang, 2010; Johns et al., 2008; Richeson & Trawalter, 2005). For example, a study conducted by Major, Eliezer, and Rieck (2012) found that overweight individuals experience social identity threat in situations that activate concerns about weight stigma, causing them to experience increased stress and reduced self-control, triggering a cascade of negative emotions, cognitions, behaviors, and biological responses. The authors asked women who varied in body mass index (BMI) to give a speech on why they would make a good dating partner. Half thought they were videotaped, which would make their weight visible, and the other half thought they were audiotaped, in which case weight would not be visible. They found that higher BMI was associated with increased BP and poorer performance on a measure of executive control when weight was visible compared to when weight was not visible. To assess cognitive resource depletion, they measured performance on the Stroop color-naming task completed just after the speech ended. The authors found that compared to the audiotaped group, the videotaped participants not only displayed greater increases in BP but also showed greater cognitive interference on the Stroop task, and retrospectively reported feeling more stress-related emotions during the speech.

This experiment shows that issues pertaining to identity-threatening situations can be investigated through the use of BP measurement. It also shows why identity-threatening situations should be avoided in the second language learning context; if sustained, it can be detrimental to learners' progress. Stigma and identity-threatening situations can have a long-term impact on a person's life, including ongoing rumination, diminished emotional self-regulation, and high BP, all tied to a potentially self-feeding mechanism. Factors that may lead to threats to language learners' identity should therefore be removed from the language classroom.

IMPORTANT CONSIDERATIONS ABOUT METHODOLOGICAL PROCEDURES

Standard Manual Recording Devices

Both manual and digital BP meters are currently employed, with different trade-offs in accuracy versus convenience. The availability of a trained experimenter, budget considerations, and purpose of the study should be considered when selecting the most appropriate instrument.

Sphygmomanometer

A sphygmomanometer is a device used to measure BP, composed of an inflatable cuff to collapse and then release the artery under the cuff in a controlled manner; it uses a mercury or mechanical manometer to measure the pressure. It is always used in conjunction with a means to determine at what pressure blood flow is just starting, and at what pressure it is unimpeded. Manual sphygmomanometers are used in conjunction with a stethoscope.

Stethoscope

A *stethoscope* is a manual option to measure BP through auscultation. Manual meters are used by trained practitioners, and, while it is possible to obtain a basic reading through palpation alone, this only provides the systolic pressure.

Mercury Sphygmomanometers

Mercury sphygmomanometers are considered the gold standard. They show BP by affecting the height of a column of mercury, which does not require recalibration. Because of their accuracy, they are often used in clinical trials of drugs and in clinical evaluations of high-risk patients, including pregnant women. A wall-mounted mercury sphygmomanometer is also known as a *Baumanometer*.

Aneroid Sphygmomanometers

Aneroid sphygmomanometers (mechanical types with a dial) are in common use; they may require calibration checks, unlike mercury manometers. Aneroid sphygmomanometers are considered safer than mercury sphygmomanometers, although inexpensive ones are less accurate. A major cause of departure from calibration is mechanical jarring, but aneroids mounted on walls or stands are not susceptible to this particular problem.

Standard Digital Recording Devices

Digital BP meters employ oscillometric measurements and electronic calculations rather than auscultation. The oscillometric technique involves a cuff that is inflated to a preset value automatically. Then, the pressure is gradually reduced, and the pressure wave causes oscillations in the vessel, which can be detected by the cuff. Digital instruments may use a cuff placed around the upper arm, the wrist, or a finger (these are in order of accuracy and inverse order of portability and convenience). Mean arterial pressure corresponds to the maximum of oscillations; an algorithm applied to the change of oscillations sets systolic and diastolic arterial pressure values. They may use manual or automatic inflation, but both types are electronic, easy to operate without training, and can be used in noisy environments. They measure systolic and diastolic pressures by oscillometric detection, employing either deformable membranes that are measured using differential capacitance, and they include a microprocessor. They accurately measure mean BP and pulse rate, while systolic and diastolic pressures are obtained less accurately than with manual meters, and calibration is also a concern.

The oscillometric method of detection used gives BP readings that differ from those determined by auscultation, and vary according to many factors, such as pulse pressure, heart rate, and arterial stiffness, although some instruments are said to also be affected by arterial stiffness or irregular heartbeats. The advantages of oscillometry are mainly the presence of reasonably accurate mean arterial pressure and the possibility of having an automated tool to determine a patient's BP at a preset interval. The disadvantages are the overestimation of low and underestimation of high values and the possibility to falsify measurements by movement.

The Palpatory Method

With the palpatory method, an inflatable cuff is wrapped around the upper arm of a participant. The manometer connected to the cuff by a tube shows the pressure applied. The experimenter feels the radial pulse, inflates the cuff until the brachial artery collapses, and there is no blood flow any more. The pressure at which a pulse can be detected again while deflating the cuff corresponds to the systolic arterial pressure of the participant. This method does not need a stethoscope or any other specific skills or equipment and can also be performed in a noisy environment. However, it only provides the systolic arterial pressure.

The Auscultatory Method

The auscultatory method is performed in a similar way; after inflation of the cuff to a pressure above the systolic pressure (verified by the vanished radial pulse), the typical Korotkoff sounds can be detected by a stethoscope applied distal of the upper arm cuff during slow deflation. The onset of the sounds corresponds to the participant's systolic arterial pressure, the last sound at decreasing cuff pressure is the participant's diastolic arterial pressure. The advantage of this technique is that it provides the diastolic arterial pressure value, and the disadvantages include the need for training how to correctly apply this technique and the need of a stethoscope and a quiet environment.

One example of a validated instrument to measure BP through this technique is the *Accutracker II* (Suntech Medical Instruments, Raleigh, NC), used for ambulatory BP monitoring. In the last few years, increasingly automated, lightweight, and accurate measurement devices have emerged. They are typically battery-powered, belt-worn, and of a size and shape similar to that of a pocket radio. Ambulatory BP monitoring units indirectly measure BP through auscultation (of Korotkoff's sounds) with piezoelectric microphones, through oscillometric measurement of the vibratory signals associated with blood flow in the brachial artery, or through the combined use of both technologies. Validation testing against mercury sphygmomanometry and intra-arterial measurement has confirmed the accuracy of these technologies.

Arterial Applanation Tonometry

A device allowing automated radial artery applanation tonometry is the *T-Line System* (Tensys Medical, San Diego, CA, USA). Arterial applanation tonometry uses a transducer strapped to an artery with a bone underneath to obtain the arterial pulse wave. This technique has been refined and now a researcher is able to assess mean arterial pressure in the radial artery, allowing the calculation of diastolic and systolic arterial pressure. The pulse wave obtained by applanation tonometry can be analyzed and contains more information than systolic and diastolic pressure alone. However, these devices are not made for continuous monitoring as they have to be handheld by the examiner.

Volume Clamp Method for Continuous BP Measurement

The second technique for noninvasive continuous BP measurement is called the volume clamp method (or vascular unloading technology). The BP is measured at the finger with an inflatable cuff combined with a photodiode. The diameter of the artery in the finger is measured by the photodiode; the pressure in the cuff is adjusted to keep the diameter of the artery constant. From the pressure changes in the cuff, a BP curve can be calculated and transferred to correspond to brachial artery BP. Devices based on this technique are *ClearSight* (Edwards, Irvine, CA, USA) and *CNAP* (CNSystems Medizintechnik AG, Graz, Austria). The continuous noninvasive devices are all sensitive to participant's movement; therefore, measurement results need to be checked for plausibility.

Photoplethysmography

BP can also be estimated optically with photoplethysmography (PPG). PPG is a simple and low-cost optical technique that can be used to detect blood volume changes in the microvascular bed of tissue. It is often used noninvasively to make measurements at the skin surface. The PPG waveform comprises of a pulsatile physiological waveform attributed to cardiac synchronous changes in the blood volume with each heartbeat, and it is superimposed on a slowly varying baseline with various lower frequency components attributed to respiration, sympathetic nervous system activity, and thermoregulation (Xing & Sun, 2016). To record PPG, a sensor (e.g., the TSD-200 from Biopac, USA) is attached on the first joint of the nondominant thumb or index finger. The signals are increased by amplifiers (e.g., the PPG-100C from Biopac, USA; Biopac's TSD-200 consists of a matched infrared emitter and photo diode detector, which transmits changes in infrared reflectance resulting from varying blood flow. When the PPG transducer is placed on the skin, in proximity to capillaries, the reflectance of the infrared light from the emitter to the detector will change in accordance to capillary blood volume; the PPG waveform peaks when capillary blood volume is maximized).

Recommendations for Data Collection

According to the American Heart Association, the following requirements should be met in obtaining subjects' BP under ordinary and reproducible circumstances. BP is taken in a quiet room at a comfortable temperature after the individual has rested for 5 minutes. Ideally, the person should not have eaten or smoked for 30 minutes prior to the BP measurement. The pressure of biological and environmental factors that affect BP should be noted. These include anxiety, distention of the urinary bladder, changes or extremes in temperature, exertion, pain, and recent smoking and food intake. Over-the-counter or prescribed medications may also influence BP measurements.

Food Intake

Experimenters should control or standardize the eating and drinking prior to experimental sessions, particularly in studies involving comparisons of different individuals or in studies involving multiple laboratory sessions.

Caffeine

Caffeine acutely affects both SBP and DBP (Lane, 1983). The effect of caffeine in healthy subjects is about 7–10 mmHg for SBP and 4–6 mmHg for DBP during rest, depending on the amount of caffeine consumed. Moreover, it is important to note that the effect of caffeine compounds with the effect of other stressors when present.

Exercise Prior to Experiment

Movements, exercise, and posture increase SBP and, to a lesser extent, DBP. Therefore, experimenters should control for the occurrence of exercise before laboratory sessions. As compared with sitting conditions, standing SBP is slightly decreased and standing DBP is slightly increased.

Time of Day

BP may also vary considerably during the day, and this variation probably depends mainly not the typical patterns of activities associated with time for any given individual, such as when they sleep, eat, relax, or exercise. Hence, experimenters should schedule laboratory sessions to control or standardize time of day or at least counterbalance for any effects related to time of day.

Emotional States

Although it can be a challenge to standardize or control for emotional states and social setting during an experiment, it is important to take them into account and obtain information about subjects' state moods and emotions through the use of state psychological scales and exit surveys.

Preparation for the Experiment

According to the *Harvard Health Publishing*, an online website dedicated to publishing information about health and sponsored by the Harvard Medical School, the following are suggestions to measure BP correctly.

Before the Measurement

The measurement should take place in a quiet environment. Before the BP measurement takes place, the researcher should ask the participant to observe the following procedures: wait 2 hours after a big meal; do not drink coffee or smoke in the preceding 30 minutes; avoid physical activity before the measurement; empty bladder and bowel if needed; sit calmly for 10–20 minutes; if possible, do not measure if uncomfortable or stressed; remove close-fitting garments from the upper arm; to avoid constriction, sleeves should not be rolled up (they do not interfere with the cuff if they are laid flat).

During the Measurement

During the measurement, the researcher should observe the following procedures: do not speak (same applies to study participant); make sure participant sits with back support; place BP cuff at mid-arm (2–3 cm above the elbow); allow participant's arm to rest at heart level; ask participant to keep the legs uncrossed and place the feet flat on the floor.

Determining Baseline BP

Registering a participant's baseline BP is important when it is necessary to compare change scores derived from groups with different baselines, or when adjustments of change scores for baseline differences is necessary. Shapiro et al. (1996), in a well-known article published in *Psychophysiology* for which they were tasked with setting BP publication guidelines, recommend that a researcher can (1) allow participants be acclimatized to the experimental environment and rest quietly for at least 20 minutes prior to the beginning of baseline measurement, during which they can, for example, wait while the experimenter calibrates the equipment; (2) discard the first few readings using a cuff because they may reflect alerting reactions to the cuff or to the experiment procedures; (3) estimate baseline BP by averaging three to five readings taken at 1–2 minute intervals, separated by quiet rest without movement or speech.

Considering Individual Characteristics

A conscientious experimenter will also keep in mind that other individual characteristics have been related to differences in BP level and reactivity, and should therefore be reported through surveys. Examples of such elements are BMI, age, sex, menstrual cycle, race and/or ethnicity, pregnancy, family health history (e.g., asthma, hypertension, heart disease, diabetes), habitual use of alcohol, tobacco, and other drugs and mediations, physical conditioning and habitual exercise, occupation, education, acculturation, current medical or psychiatric treatment, personality, coping styles, work and family stress, and social support.

Recommendations for Data Processing

Signal Analysis

After data collection, a number of post-processing steps on the data should be performed. The data obtained through any instrument must be edited for artifacts and outliers using the instrument's manufacturer's software error codes and following set rules. Acceptable SBP readings may range from 75 to 200 mmHg, and acceptable DBP from 40 to 120 mmHg. If one measure is excluded, the other must also be removed.

Statistical Analysis

The post-processed data then will be ready for statistical analyses (e.g., descriptive statistics, correlations, etc.). In designing statistical analyses for their data, researchers should decide what is appropriate based on the nature of the data and goal of the study.

Chapter 4

Electrodermal Activity

A BRIEF OVERVIEW OF ELECTRODERMAL ACTIVITY

Electrodermal activity (EDA) is an umbrella term used for defining autonomic changes in the electrical properties of the skin. This term was first introduced by Johnson and Lubin (1966) as a common term for all electrical phenomena in the skin. Historically, various terms for skin electrical activity have been used (along with their widely used abbreviations) as skin conductance (SC), galvanic skin response (GSR), electrodermal response (EDR), psychogalvanic reflex (PGR), skin conductance response (SCR), sympathetic skin response (SSR), and skin conductance level (SCL). The long history of research into the active and passive electrical properties of the skin by a variety of disciplines has resulted in different names, but it is now more common to refer to these as EDA for the sake of interdisciplinary clarity. The use of EDA measurements is quite popular in human behavior research across several disciplines due to its low cost, extremely fast setup time, and noninvasive procedures for data acquisition.

EDA is probably the most useful index of changes in sympathetic activation influencing emotional and cognitive states as it is the only autonomic psychophysiological variable that is not contaminated by parasympathetic activity. EDA has been closely linked to autonomic emotional and cognitive processing, and it can also be used to examine implicit emotional responses that may occur without conscious awareness or are beyond cognitive intent (i.e., threat, anticipation, salience, novelty). Recent research has shown that EDA is also a useful indicator of attentional processing, where salient stimuli and resource-demanding tasks evoke increased EDA responses.

The most common applications of EDA found in the literature include orienting responses and habituation processes, autonomic conditioning, biofeedback, psychophysiological detection of concealed information, autonomic arousal, attention, temperament or personality, psychopathology (particularly schizophrenia and psychopathy), emotion, and, more recently, the role of emotions in decision-making. This coupling between cognitive states, arousal, emotion, and attention enables EDA to be used as an objective index of emotional states. EDA can be used to examine implicit emotional responses that may occur without conscious awareness or are beyond cognitive intent (i.e., threat, anticipation, salience, novelty). Recent research has shown that EDA is also a useful indicator of attentional processing per se, where salient stimuli and resource-demanding tasks evoke increased EDA responses. Investigations of EDA have also been used to illuminate wider areas of enquiry such as psychopathology, personality disorders, conditioning, and neuropsychology.

EDA has a long history of being used in psychological and physiological research. Since the 1880s, when psychological factors related to electrodermal phenomena were first observed, electrodermal recording has become one of the most frequently used bio-signals in psychophysiology. One major reason for its popularity is the ease of obtaining a distinct electrodermal response with an intensity that seems to be related to the intensity of the stimulus, and another factor being that it requires fairly inexpensive equipment. In addition, recording is not limited to a laboratory, and can be done in less controlled environments.

Recent improvements in technology, methodology, and reporting have meant that EDA has become an increasingly important variable in psychological science. These improvements have also led to further refinements in analysis techniques and the methods used for handling EDA data and making it fit for final analysis and interpretation. Such advancements also leave room for some controversies over how EDA should be analyzed in given circumstances.

The Role of Sweat in Thermal Regulation of the Body

EDA measures activity of sweat glands, under control of the sympathetic nervous system. The human body has about three million sweat glands dedicated to thermoregulation, the greatest density being found on the palms, soles, and forehead, and the least density on the arms, legs, and torso. In humans, thermoregulation constitutes a phylogenetically highly developed autonomic system with impacts on kidney and cardiovascular functions. The power of this system can be illustrated by its reaction to stress, where under extreme circumstances, secretion at rates of up to 2 liters of sweat per hour can be observed; this is equivalent to one-quarter of the total fluids in a whole body during a single day of sustained stress.

Five Nonthermal Types of Sweat

Besides thermal sweating, there are five additional kinds of sweating, and these groups are formed based on the stimuli eliciting them. All of them use the postganglionic sympathetic neuron, which has its origin in the sympathetic trunk and travels via the peripheral cutaneous nerve to the sweat gland as a final common terminal path. However, they differ in terms of elicitation mechanisms. The five nonthermal types of sweating are (1) emotional sweating, elicited by psychological and emotional states; (2) gustatory sweating, when consumed food is highly spicy, salted, or sour; (3) ubiquitous spontaneous sweating, observed in smaller amounts than the other kinds of sweating, mainly on palmar and plantar sites, and it is involved in muscle resting tonus; (4) reflect sweating, occurring at sites innervated from spinal cord segments distal to the locus of certain damage; and (5) pharmacologically induced sweating.

Sweating as an Expression of Sympathetic Arousal

Sweating is controlled by the sympathetic nervous system, and in the absence of the other triggers of sweat listed above, electrodermal activity is an indication of psychological or physiological arousal. If the sympathetic branch of the autonomic nervous system is highly aroused, then sweat gland activity also increases, which in turn increases SC. Due to this property, EDA is one of the most useful indexes of changes in sympathetic arousal.

Components of Electrodermal Activity

There are two main components to the overall complex referred to as EDA. The EDA complex includes both background tonic (SCL) and rapid phasic components (SCRs) that result from sympathetic neuronal activity (see table 4.1). Changes in the SCL are thought to reflect general changes in autonomic arousal. SCRs relate to the faster changing elements of the signal. Tonic activation refers to shifts in the overall baseline of activity, whereas phasic activity refers to fluctuations over time, which may occur spontaneously or in response to an event. Recent evidence suggests that both components are important and may rely on different neural mechanisms (Dawson et al., 2001; Nagai et al., 2004). According to Benedek and Kaernbach (2010), the slowly varying tonic activity can be contrasted to the rapid spikes of phasic activity that can be attributed to sudomotor nerve responses within a 1–3 second window following the stimulus, depending on individual reactivity. A phasic response would be expected to return to its tonic baseline and can be succeeded by other fast-varying phasic responses.

Table 4.1 ***Electrodermal Components***

Measure	*Description*
Skin Conductance Level (SCL)	SCL refers to the tonic level of electrical conductivity of skin
Skin Conductance Response (SCR)	SCR refers to the phasic change in electrical conductivity of skin
Nonspecific SCR (NS-SCRs)	Nonspecific SCRs are the ones that occur in the absence of an identifiable eliciting stimuli
Frequency of NS-SCRs	The frequency of NS-SCRs is the rate of NS-SCRs that occur in the absence of identifiable stimuli
Event-related SCR (ER-SCR)	ER-SCRs are the SCRs that can be attributed to a specific eliciting stimulus

Source: Table created by author.

EDA increases following an arousing stimulus are slow and are typically detectable on a scale of seconds. Relatedly, they also differ with respect to the tonic and phasic components of their activity. Additionally, tonic and phasic activity may interact, such that phasic responses may only occur at certain tonic levels of arousal activity.

The use of the term "response" for phasic electrodermal phenomena suggests that there is a relationship to the stimulus producing the response. But there are some phasic parts of EDA that cannot be traced to any specific stimulation. For this reason, they are called "spontaneous" or "non-specific" EDRs. The measurement of exosomatic EDA with DC, using a constant voltage system, is the most widely applied method in psychophysiology for observing both phasic and tonic electrodermal phenomena.

ELECTRODERMAL ACTIVITY AND LANGUAGE RESEARCH

The fields of applied linguistics and linguistic anthropology have a longstanding interest in the role of the body in interaction. Discourse and conversation analysis have long been concerned with the fine-grained texture of interaction itself (Goodwin, 2007; Gumperz, 1982), its underlying motivations and psychological states, and the intricate choreography of the participating bodies with aspects of language (Goodwin & Cekaite, 2018), intonation (Couper-Kuhlen, 2003), gestures and touch (Goodwin, 2017), or gender differences (Goodwin, 2006; Tannen, 1984, 1990). Gail Jefferson (2004) considered gender not as a given entity belonging to an individual, but rather as a career, a cumulative trajectory through which individuals play out all their interactions. Such bodily displays are paired with linguistic choices and distinct behavioral patterns in a conversation, and such social engagement behaviors can be correlated with sympathetic responses, measurable with EDA recordings. For example, a study conducted by Mendoza-Denton, Eisenhauer, Wilson, and Flores (2017) made use of EDA to investigate the affective dimensions of videogame players' interactions among male and female players. Through the analysis of gameplay interaction, talk, laughter, gesture, and participants' EDA, these authors showed that the design of the game itself and the entanglement of hardware and software design with gendered gameplay were shown to marginalize and exclude female participants.

Another good example of how using EDA recordings can help expand our understanding of co-operative action in multimodal discourse analysis (Goodwin, 2018) is a study conducted by Stevanovic et al. (2019). They examined the emotional and psychophysiological underpinnings of social interaction in dyadic conversations. In their experiments, half the dyads were neurotypical participants (NT/NT), and the other half comprised of one neurotypical participant and one participant that had been diagnosed with Asperger syndrome (NT/AS). All participants were male. They recorded participants' autonomic nervous system activation through the measurement of participants' electrodermal activity, heart rate, heart rate variability, as well as facial muscle activation during conversations. Then each participant's affiliative and dominant behaviors during the first and last 10 minutes of the conversations were assessed by three independent raters. The authors found that, in the NT/NT dyads, a high level of affiliation displayed by the conversational partner calmed down the participant when they were actively dominating the interaction. By contrast, when the participants themselves expressed affiliation, their psychophysiological responses indicated increase in arousal, which suggests that the giving of affiliation is physiologically stressful, as in doing "hard work" (Goldberg, 1978; Goodwin, 1981) The affiliation-related ANS responses were similar in those neurotypical participants whose conversational partner had Asperger's, while some differences in facial muscle activation did occur in comparison to NT/NT dyads. However, a high level of affiliation provided by the conversational partner was associated with increase in arousal in the participants who had Asperger's, suggesting that experienced elicited alertness and stress. As for their own affiliative behavior, the Asperger's participants exhibited similar indicators of alertness and stress as the NT participants, but only when their own level of dominance was low. These results increase understanding of how individuals with Asperger's experience social interaction at the physiological level, and how this experience differs from that in neurotypical individuals. Moreover, these results confirm that affiliation during dyadic conversation involves the type of a mental "sharing of the burden" (Goodwin, 2017) that also reverberates in the participants' bodies.

Electrodermal activity can also help language studies with a pedagogical approach look for ways to improve students' learning experience or to understand learning (or the absence of learning) outcomes. One example of what can be accomplished through the use of EDA wireless recorders is the investigation of physiologically based automated detection of mind wandering during learning. A study conducted by Blanchard, Bixler, Joyce, and D'Mello (2014) showed that mind wandering can be detected by monitoring physiological measures of SC and skin temperature. In this study, they asked seventy participants to wear an Affective Q Sensor strapped to the inside of their nondominant wrist and sit in front of a computer to study four texts, each on key research methods topics: experimenter bias, replication, causality, and dependent variables. On average, each text contained 1,500 words with approximately 60 words per page. Students were informed that they would be asked a series of test questions on each text after reading. As students progressed through the texts, they were instructed to report if they were mind wandering by responding to auditory probes. The authors acknowledge that their detection rates are modest, but proposed this to be an unobtrusive detection of momentary instances of mind wandering, an elusive state that is difficult to study since it is a highly internal unconscious phenomenon.

IMPORTANT CONSIDERATIONS ABOUT METHODOLOGICAL PROCEDURES

As discussed earlier, a rise in EDA levels is controlled by the sympathetic nervous system. While a rise in EDA can be a reaction to physical stimuli, it is sensitive enough to register reactivity to psychological stimuli like positive and negative emotions, engagement, and intense focus. While EDA on its own cannot inform researchers of the cause or valence for a response, it can be used to indicate where during an experiment there were sustained high or low levels of sympathetic response.

Direct Current Measurements

The measurement of EDA can use a direct current (DC) constant voltage methodology with silver-silver chloride (Ag/AgCl) electrodes and an electrolyte of sodium or potassium chloride. This recording method has dominated the EDA literature for many decades. This basic method applies a small voltage (e.g., 0.5 V) to two electrodes placed on the intact palmar surface of the skin and a small resistor (e.g., 200 to 1000 W) in series with the skin. The electrodes should be placed on the same body side to avoid electrocardiogram (ECG) artifacts. Because the resistance of the skin is of the order of 100 kW

(1 kW = 1000 W) or more, the small series resistor is considered negligible with respect to affecting the current flow in the circuit and can be ignored when measuring current flow.

Alternating Current Measurements

The measurement of EDA with alternating current (AC) instead of direct current (DC) has been rather infrequently used so far, despite having the property of circumventing some problems with using DC for conductance measurement. That is because the electrodes become polarized by DC current flow. Polarization refers to the counter electromotive force that is generated at the electrode metal surface, as a result of which the electrodes behave like a rechargeable battery, with a voltage opposing the applied voltage. The use of so-called nonpolarizing electrodes may partially prevent polarization during DC recording. By contrast, electrode polarization is virtually eliminated when AC measurement is used. Because it continuously changes its polarity, AC polarizes the electrodes to a much lesser extent than DC. As a result, the electrolysis occurring before the polarity changes is negligibly small. For these reasons, AC measurement appears to be superior to DC measurement with respect to electrode polarization and also possible effects of the applied voltage on biological membranes.

Exosomatic Electrodermal Activity Recordings

Exosomatic recordings apply to the skin either direct current (DC) or AC. The measurement of exosomatic EDA with direct current, using a constant voltage system, is the most widely applied method in psychophysiology for observing both phasic and tonic electrodermal phenomena.

Endosomatic Electrodermal Activity Recordings

In endosomatic measurements, only potential differences originating in the skin itself are recorded without using any external source of current. The measurement of endosomatic electrodermal responses (EDRs) is the most unobtrusive method and may differentially reflect the various processes taking place during phasic EDA.[1]

Units Used to Measure Electrodermal Activity

EDA is measured in microsiemens (μs), which is a standard measurement of electrical conductance, or the micromho (μmho); both units are equivalent, and 0.0c1μS is equal to 1μmho.

Standard Recording Devices

Technology in this area has seen a very rapid growth in the last decade alone. Recorders and transmitter are becoming smaller and more portable. The following description of recording devices offered by various leading manufacturers in the field is only a limited sample of the options available today. Nevertheless, it aims at providing a starting point for researchers, bearing in mind that it is possible that within few years from the publication of this book, this information is going to become obsolete.

Biopac EDA Recorders

In order to record EDA, the researcher can use Biopac's data acquisition systems MP36R or the MP160 in conjunction with their native software *AcqKnowledge* and Biopac electrodes, amplifiers, transducers, and other system components. Biopac's EDA recorders produce exosomatic (DC) measures of SC used. The MP36R offers 4-channels, each of which can be configured to sample up to 100,000 samples/sec. It utilizes a 24-bit A/D converter making it the fastest sampling and most sensitive device of its type currently available. The device is completely configured to interface with *AcqKnowledge*, and it can be interfaced directly to a computer responsible for stimulus presentation so that EDA correlates of specific stimuli can be tagged and detected.

However, if a researcher needs more than four channels, the MP160 system is the better choice as it offers sixteen channels. The MP160 offers multiple configurations to suit individual research needs and records multiple channels with differing sample rates at speeds up to 400 kHz (aggregate). MP160 systems are Ethernet-ready and compatible with Biopac system components, as well as many leading equipment brands, and support a wide range of wireless and wired signal-specific amplifiers.

Finally, the existence of multiple channels means that EDA measurements can be simultaneously complemented by additional psychophysiological measures, or paired with the psychological measures of other participants performing the same experiment at the same time. Data from the MP36R and MP160 can also be time-linked to concurrent video recordings, where both can be played back in concert or parallel.

Empatica E4 EDA Recorder

The Empatica E4 is an example of a wearable wireless multisensor device for real-time computerized biofeedback and data acquisition. In the form of a wristband, it is a device that offers real-time physiological data acquisition and software for in-depth analysis and visualization. It has four embedded sensors: it integrates a PPG sensor to measure blood volume pulse from which heart rate variability can be derived, a three-axis accelerometer to capture motion-based activity, an EDA sensor, and infrared thermopile to read peripheral skin temperature, and internal real-time clock with temporal resolution of 0.2 seconds in streaming mode through Bluetooth, and an event mark button to tag events and link them to physiological signals. It uses flash memory, and it can record up to 60 hours of data with 5s synchronization resolution. Through E4 connect, you can view and manage data on a secure cloud platform; but it is also possible to download raw data in CSV format for posterior processing and analysis in third-party applications. Data is secured with encryption and can be deleted after use. Empatica gives you the option to visualize real-time data when the E4 wristband is connected via Bluetooth to smartphones and tablets. Once the session ends, data is automatically uploaded to the user's Empatica Connect account. Alternatively, it is possible to download data via USB and transfer it to a computer. With the E4, it is possible to conduct research outside of the lab by acquiring continuous data for ambulatory situations in a comfortable and nonintrusive way.

The E4 is equipped with a peripheral board for EDA circuitry that, when worn, it is placed on the ventral area of the wrist. The terminal part of the EDA sensor is composed of two silver-coated (Ag) electrodes. A small AC is applied to the skin through the electrodes. The Ag electrodes are hypoallergenic and durable, and the E4 supports periodic electrode replacement and affords researchers the opportunity to use custom electrode materials or lead wire extensions to support traditional electrode placement, if desired. EDA is typically described as a combination of two components, the SCL and the SCR. The E4 has an innovative technology that accurately records SCL while maintaining sufficient sensitivity to distinguish the SCR under any condition. High-resolution EDA data can be used by researchers for measuring sympathetic activation, a biomarker of autonomic stress.

While nowadays it is possible to find a large number of other wearable devices that measure data related to health, not all of them provide high-resolution quality sensors. In addition, the E4's photoplethysmography (PPG) sensor uses an artifact removal technique based on a combination of multiple wavelengths.

Recommendations for Data Collection

Recording Sites

Because non-thermoregulatory electrodermal phenomena can be most reliably and validly recorded from the skin of the palms and the soles, they constitute the preferred recording sites for EDA. Active electrodes are fixed either to the volar (i.e., inner) medial or distal phalanges of the fingers, or to thenar and hypothenar sites on the palms of the nondominant hand (see figure 4.1, diagram I).

The distal phalanges of the fingers (see figure 4.1, diagram II) should be preferred because of their greater responsivity (Scerbo, Freedman, Raine, Dawson, & Venables, 1992) and their greater sweat gland activity as compared to the medial and proximal phalanges (Freedman et al., 1994). For palmar endosomatic recordings, the inactive electrode is placed on the volar surface of the forearm, marked with the latter E in figure 4.1 (diagram II).

Recently, the volar (i.e., inner) side of the wrist has been used for electrodermal recording, especially when the whole EDA recording system was located in a wrist device. However, these sites are not recommended because they may be affected by thermoregulatory rather than electrodermal phenomena.

If both hands are unavailable (e.g., if they are needed for computer work), Edelberg (1967) recommended two sites at the inner aspect of the foot, over

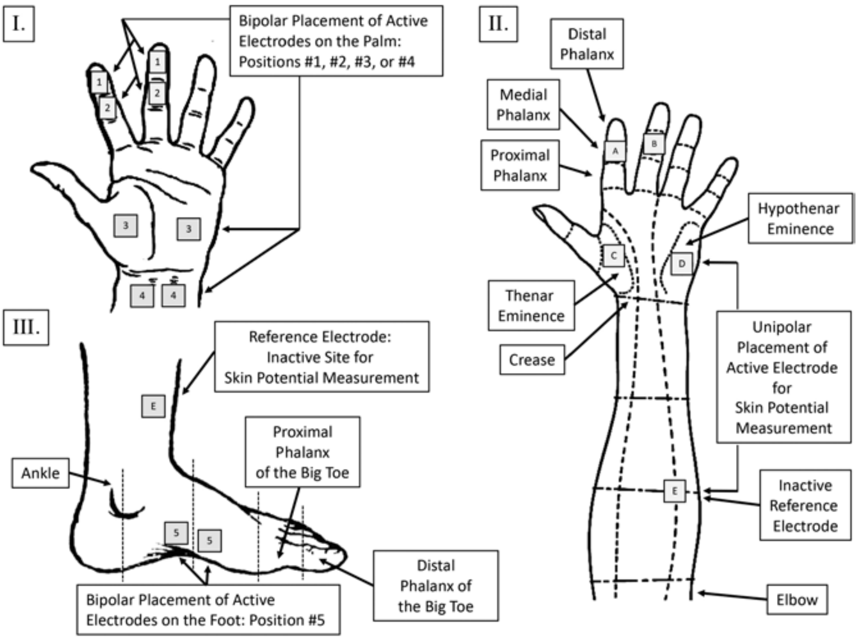

Figure 4.1 Placement of Electrodes on Palm, Forearm, and Foot. Diagram I Shows the Bipolar Placement of Active Electrodes to the Distal Phalanges (position #1), to the Medial Phalanges (position #2) and to the Volar Thenar and Hypothenar Sites on the Palm (Position #3). Diagram II shows the location of the phalanxes and the thenar and hypothenar eminences on the palm, and the placement of unipolar electrodes along with an inactive site for skin potential measurement. Diagram III shows the bipolar placement of active electrodes on the foot. Position #D should be used for exosomatic recording while position #E should be used as the inactive site for endosomatic recording. *Source*: Diagram created by author.

the abductor hallucis muscle adjacent to the sole of the foot and midway between the proximal phalanx of the big toe and a point directly beneath the ankle, for active electrodes, whereas in the case of endosomatic recording, the inactive electrode is fixed above the ankle (see figure 4.1, diagram III).

Pretreatment of Sites

There is normally no need for pretreatment of active recording sites, but the sites may be washed with lukewarm water prior to the electrode attachment. Washing with soap is not recommended because it may cause swelling of the epidermis. Precautions should also be taken in using 70% ethanol because it may change the epidermal salt concentration. The latter may be necessary in case of extremely oily skin for preventing detachment of the adhesive tape used for electrode fixation.

Slight abrasion of the skin, which was a recommended procedure for pretreatment of electrodes affixation sites in the past, essentially eliminates all potential and thus provides electrical contact with interstitial fluid. In principle, such abrasion could be limited to the corneum, but because of the risk of deeper penetration, abrasion is only recommended when using sterile electrodes to avoid the danger of transmitting diseases such as HIV or hepatitis. An unabraded site on the volar forearm about two-thirds of the distance from the wrist to the elbow provides a relatively inactive reference site. Some manufacturers do not recommend abrading the fingers before placing the electrodes.

Electrodes

Electrodes for electrodermal recording are normally made of metal, but they can also be from other materials such as carbon. “Metal” is used here as a generic term, as it actually gets corroded at the electrode surface. It is important to use the same metal for the two electrodes in a DC-recording system, because a potential difference will be generated by different metals, different stages of corrosion, or both, which causes a counter electromotive force, and thus electrode polarization. Furthermore, pairs of electrodes should show a minimal bias potential, which can be measured in the absence of an applied voltage. The most widely used EDA electrodes contain a metal disc set back in a cylindrical plastic case, which is filled with electrode gel.

Electrode fixation is improved with adhesive tape or a foam ring around the electrode. Securing the electrode metal back (recessed) in the electrolyte compartment helps to avoid motion artifacts, which might result from the electrode fixation to the skin and the skin curvature at the recording site. It also helps reduce artifacts from movement between gel and electrode metal. Additional tape may be necessary depending on measurement conditions, especially with skin that is wet from sweating. Some electrode constructions involve electrolyte contained in a stiff cup so that outside pressure on the electrode will not squeeze out electrolyte, which otherwise would increase the electrode's effective area and penetrate into the adhesive area.

The effect of any pressure, such as that exerted by fixation, the weight of the electrode, and protruding parts (e.g., wires), must be kept as low as possible. The recommended wiring is to use prewired electrodes with a plug or connector to the amplifier remote from the electrode. The electrode wire should not be able to exert any pull on the electrode, irrespective of its hand or foot position. For this purpose, the electrode wires can be fixed by tape to the skin, for example, 10–15 centimeters from the electrode, and there should be given an extra wire loop between the electrode and the first skin fixation.

Disposable electrodes may have some important advantages. They can be hygienic, hypoallergenic, antiseptic, and latex-free. They can have a good fixation system, be stored many months in an unopened package, be produced in large production runs with uniform electrical characteristics, and have a snap-action connector or, even better, be prewired with the connector remote from the electrode. Pre-gelled models have the additional advantage that the metal–electrolyte interface is stabilized and ready for use. Lastly, the gel must be EDA compatible (ECG or EEG paste will not work).

The choice of electrode type, wiring, and electrolyte is dependent on the intended use. Measurement durations on the order of 30–60 minutes under close supervision are more typical, but continuous monitoring for a few days may require different methods of electrode technique (for more information on methods for longer periods of continuous monitoring, see Boucsein et al., 2012).

Electrode Contact

Good electrode contact is essential for high-quality EDA data. It is generally recommended that sufficient time between attaching electrodes to the skin and gathering the data be provided. This is to allow for the gel to become sufficiently absorbed over the measurement area and to allow for the participant to be relaxed and ready for the experiment. Approximately 5 minutes would be sufficient in most cases. Some preliminary measurements should also be taken to assess electrode contact before the experimental measurements are taken. During this period, researchers can request the participant take some sharp and deep breaths to ensure good connectivity and EDA responsiveness. Once done, if the responses are of good quality, discard these data and begin the experiment.

Electrolytes and Skin Contact Area

The contact electrolytes are usually NaCl or KCl in the form of a wet gel or paste. For EDA recording, electrode gel or paste must contain a chloride salt, with NaCl being most often used. Concentrations in the range of 0.050–0.075 molar (0.3%–0.4% by weight) are preferred, because they approximate the concentration of NaCl in sweat that reaches the surface. As a result, any sweat that mixes with the paste is unlikely to appreciably alter the concentration of the NaCl at the interface with the electrode. In ECG recording, the salt may have a concentration of 3% by weight (0.5 M), not far from sea water that is well tolerated by our skin for many hours. Such salt concentrations are far too high for EDA recordings; therefore, pre-gelled commercially available ECG or EEG electrodes are not suitable for EDA recording.

Baselines

It is often good practice to run a baseline measurement period when the participant is not engaged in any given task. The general recommendation is to use between a two-minute to four-minute baseline session. Such sessions can also help inform as to whether certain participants are likely to be hyper or hypo-responders independent of any effects of psychological manipulation. From this, the researcher can measure the frequency of NS-SCRs (as a measure of EDA responsiveness in the tonic SCL), and the average amplitude of these NS-SCRs.

In addition to any baseline conditions the experimenter may use, it is advisable that one allows for a baseline period within any given experimental signal. This can be at the beginning of the signal recording, at the end, or both. We recommend a 60 second (minimum) period be provided within any given signal and it is more commonplace to assign this period to the beginning of the measurement period. The purpose of this period is to facilitate the calculations the software needs to make. Some routines require a moving window to pass through the signal to make calculations, and it is from these calculations that accurate deviations can be established. The integrity of this process is optimized if a sufficient baseline period is provided within the signal being analyzed. In addition, it provides a baseline SCL measurement right at the time leading up to, and just before, the very start of the experiment.

Recommendations for Data Processing

Most studies using electrodermal measures take place in laboratories, where experimental conditions are carefully controlled. In this setting, standardized stimuli can be presented and the reactions of the experimental participant meticulously measured. Laboratory recording is limited in that the laboratory affords only an artificial representation of everyday life, and the time that a participant is willing to spend in the laboratory during waking periods is seldom more than 2 hours.

On the other hand, when situations are not structured, and participants do their normal activities, uncertainty arises as to what to attribute variations in electrodermal activity. For example, a socially engaging conversation or an interesting new environment may cause fluctuations in SCL as great as might be elicited by stress or fear. Simultaneous video and audio recording or frequent self-reports might be necessary to understand the psychological meaning of those fluctuations. Intermediate between a 2-hour laboratory recording and an uninterrupted 24-hour recording period are structured situations with predictable timing, during which activities such as driving, working, and sleeping are performed.

Technical developments in the last few decades have made ambulatory recording of electrodermal activity ever easier. Several manufacturers have produced portable multichannel physiological recorders that include an electrodermal activity channel. Ordinarily two electrodes are placed on the hand or fingers and cables go up the arm and down the trunk to a battery-powered amplifier-digital recorder attached to the waist, like the Biopac's Bionomadix system of wearable wireless devices. A company called Empatica makes a device where the amplifier-recorder is worn on the wrist like a watch with a dry electrode in contact with skin on the ventral wrist.

Identifying and Removing Artifacts Stemming from Recording

Disruptions of the skin-electrode interface can be caused by mechanical pressures on the electrodes, loose electrodes, wire drag, flow of gel, and changes of the skin below the gel caused by the gel. Further sources of artifacts are gross body movements, speech, irregular breathing, and also influences from outside the participant such as ambient noise or other disturbing stimuli.

It is desirable to review the record visually so that portions containing artifacts can be excluded from analysis (see Boucsein, 2012, pp. 183–186). In recordings less than 2 hours long, it is advisable to scan the entire record visually and to exclude segments containing artifacts.

For ambulatory recordings, help from programs that detect artifacts is advisable. Such programs can locate segments where SCL levels exceed thresholds set for each participant and inform the operator to visualize these epochs and exclude them if they contain artifacts. Even in case of computer-assisted artifact detection and removal, it is advisable to visually inspect the detected suspicious SCRs and accept them or reject them as artifactual (Boucsein, 2012, p. 526). In any case, even semi-automated artifact removal procedures are time-consuming. Therefore, artifact avoidance should be given priority.

When required to record several hours or more, another recommended precaution is to compare measurements from old and fresh electrodes to detect possible artifacts resulting from electrode deterioration.

Identifying Artifacts Stemming from Participant's Physiology

Emotional effects on electrodermal activity are more sensitively recorded from electrodes on the palmar surface of the fingers or hand than from the ventral wrist, which is more affected by thermoregulatory changes. Ambient temperature and physical activity should be recorded simultaneously with EDA to allow for exclusion of periods where environmental temperature is significantly higher or lower than average and during and immediately after periods of strenuous activity. The effects of psychologically significant events and states during recording can only be understood if these events and states are assessed in synchrony with electrodermal measures. Participants should be able to report with button or key presses when such events or states occur.

There are wide individual differences in both tonic and phasic EDA related to demographic variables such as *age*, *gender*, and *ethnicity*. For example, older adults generally have lower tonic arousal levels and smaller phasic responses than do younger adults when tested across a wide range of ages (e.g., between 20 and 60 years of age). The effects of age may be due to peripheral or central nervous system changes with age, or both. At the periphery, the number of active sweat glands is lower in older adults (mean age of 69.5 years) than in younger adults (mean age of 25.3 years), which may partially account for the lower tonic and phasic findings (Catania, Thompson, Michalewski, & Bowman, 1980). Aging is also generally associated with reduction of brain gray matter including areas important for electrodermal activity (i.e., cortex, hippocampus, amygdala, and hypothalamus; Sequeira & Roy, 1993). Gender differences also have been reported in tonic and phasic EDA, although the size and direction of the effects seem to vary depending on the nature of the stimulus situation. For example, women have been found to show larger SCRs to unpleasant pictures than men (Bradley, Codispoti, Sabatinelli, & Lang, 2001). Ethnic differences have also been observed in EDA. For example, early research found higher resting SRL (lower SCL) in African American children (mean age 7 years) and adults (mean age 22.9 years) than in age-matched Caucasian American children and adults (Johnson & Corah, 1963).

Identifying Artifacts Stemming from External Variables

Certain external environmental variables such as temperature and humidity have been investigated as sources of variance in EDA. Although the hands are not principal areas of thermoregulatory sweating, the effects of temperature on EDA have been studied in various ways, including manipulation of body temperature, manipulation of ambient temperature, correlation with ambient temperature, and correlations with seasons of year. Long-term ambulatory recording of SC outside of a temperature-controlled laboratory has also found EDA measures to be positively correlated with changes in ambient temperature. Outside temperatures change with season of year and may influence EDA even when tested within the laboratory. All in all, although palmar eccrine sweat glands are not as sensitive to temperature as those on other body sites, they are definitely influenced by temperature. Therefore, in the laboratory study of EDA, it is important to keep temperature as constant as possible and, in studies outside the laboratory, it is important to statistically correct for differences in ambient temperature. Other variables to take into account are relative humidity and use of medication by the participant.

Acquisition Rates

Any digital recording of an analog signal is composed of samples acquired at discrete time points. Most A/D converters acquire samples at regular intervals. The timing can be described by that inter-sample interval, or by its reciprocal, the number of samples acquired per unit time. This sample rate can be set quite low for long-term ambulatory measurements or experiments that do not require a high level of temporal precision (i.e., 1–5 samples per second). However, if the researcher wants to run an event-related analysis—where significant deflections in the EDA signal need to be precise and tied to stimulus presentations on a computer screen, then 1 millisecond accuracy is required. Lower sample rates cannot ensure this trigger event is accurately represented in the measurements and a degree of timing error might occur. To avoid this, we recommend the acquisition rate be set to a minimum of 2000 samps/sec (2KHz). This will equate to 2 samples per millisecond thus ensuring 1 millisecond accuracy between the computer presenting the stimulus (via presentation packages like E-prime) and the trigger sent to the computer recording the EDA. Note that acquisition rates have implications for the individual channel sample rates (discussed below) that will be available to the operator. It is up to the operator to ensure that the acquisition rates implemented allow for the appropriate channel sample rates for the desired psychophysiological measures.

Channel Sample Rates

Higher sample rates are useful for a number of methodological reasons and for improvements in precision. The Nyquist theorem would require sampling at twice the maximum frequency of expected events. For EDA it is typical to filter the data at 35Hz and so this would represent a theoretical maximum frequency. Therefore, some might argue a sample rate of 70 samples/sec is all that is required. However, the Nyquist theorem is not the only factor one should consider when selecting an appropriate sample rate. For example, some recommendations are that a sample rate of 200–400Hz is a minimum to ensure enough samples for accurate separation of phasic waveforms from tonic signals (Ohira & Hirao, 2015) and a more accurate representation of signal shape. If the researcher is interested in exploring both factors independently–then sample rates in these regions are considered a minimum.

Recently, modern algorithms for delineating and separating phasic components from each other (if they happen in close succession) are better satisfied by a higher sampling of the signal (i.e., deconvolution/negative deconvolution methods), as are calculations for areas under the curve. Thus, the intended analysis must also be taken into account when deciding on sample rates. Furthermore, sometimes it is necessary to smooth a signal due to factors such as noise, sudden deflections, and so on. However, some signal smoothing algorithms require down-sampling. Such down-sampling is always going to be restricted if the original sample rate was itself quite low. With high sample rates one can remove a host of artifacts without altering the signal shape markedly and still have plenty of samples remaining for an appropriate analysis (the ideal scenario). As a consequence of these observations, a general approach is to always err on the side of caution and probably seek to sample higher than you really need. The old adage is that the researcher can always remove samples if they have too many, but you can never put samples into the signal if they were not there originally. As a general guide, in our laboratory, we have sampled EDA at 1000 Hz, 2000 Hz, and 5000 Hz to explore signal integrity under a variety of experimental conditions. The latter is excessive and provides little obvious advantage over both lower sample rates. As a general rule 1000–2000 Hz sample rates are more than sufficient and are easily achievable for contemporary devices.

NOTE

1. For technical information about ideal settings of various recording devices for endosomatic recording, exosomatic recording with direct current, exosomatic recording with alternating current, and ambulatory monitoring, please refer to Boucsein et al.'s (2012) article providing recommendations for electrodermal activity measurements.

Chapter 5

Skin Temperature

A BRIEF OVERVIEW OF SKIN TEMPERATURE

Being the largest sensory organ in the human body, the skin serves as a barrier between the internal body and the external environment, allowing the constant maintenance of homeostasis. Homeostatic control of cutaneous temperature is functional for both biological and psychological reasons, such as to adapt to an environmental change, to fight a virus (e.g., fever; Skitzki, Chen, Wang, & Evans, 2007), or to support physiological demands in case of an external threat (Porges, 2001). However, temperature control associated with emotional reactions is far more complex as it serves a different purpose, has distinct neuroregulatory systems, and carries its own thermal processes.

The microcirculation of the skin is mainly controlled by sympathetic activity and is often used experimentally as a measure of sympathetic activity because arterioles, especially those of fingertip skin, only have sympathetic, adrenergic constrictor nerves. For example, a study conducted by Kistler, Mariauzouls, and von Berlepsch (1998) demonstrated that decreases in microcirculation induced by stressors or other stimuli acting on the sympathetic nervous system were correlated with temporary decreases in fingertip temperature. Various stimuli induced almost immediate temporary vasoconstriction, measured by laser Doppler flux and pulse volume, provided that the starting fingertip temperature was above 32 degrees Celsius. This temporary decrease in fingertip temperature had a lag phase of approximately 15 seconds and occurred when vasoconstriction lasted at least 5 seconds. Infrared thermography clearly demonstrated that sympathetic mediated changes in cutaneous microcirculation were most prominent in fingertip skin.

Variations in Skin Temperature in Different Parts of the Body

When sitting in an environment with a comfortable temperature, the temperature of the skin surface varies in different regions of the body. For example, the temperature of the skin surface of the torso usually varies between 92 and 98 degrees Fahrenheit (which is equivalent to 33 to 37 degrees Celsius). The temperature of the skin surface is lower over superficial veins than the temperature over superficial arteries; it is also lower over protruding and curved parts of the body, such as the nose, ears, fingers, and toes; it is higher over muscles than over bone or tendons; and it is higher over an active organ compared to one at rest. As a rule, stout persons, due to having a thicker layer of subcutaneous fat, have a much lower skin temperature than thin individuals. In general, the temperature of the skin covering the extremities is lower than that of the skin covering the head and torso, and it is the skin temperature of the body extremities that sees that biggest fluctuations when the body is exposed to changing environmental temperatures. Where there is a chance that the body temperature may rise because of an increase in metabolism or because of the high temperature of the surrounding environment, the skin temperature of the extremities increases so that it may approach or actually reach the same temperature level as that which exists over the head and torso. Upon exposure to cold, the skin surface temperature of the extremities becomes much lower than that of the rest of the body. However, while the temperature of the exterior of the body may vary widely, the temperature of the interior varies between more narrow limits. It has been shown that the variations in skin blood flow and blood temperature are most influential on hand skin temperature.

Influence of Age on Skin Temperature

Age has an influence on skin surface temperatures. With old age, the temperature becomes lower and basal metabolism diminishes with increasing years. The heat regulating apparatus is not fully developed at birth and is almost completely absent in the premature infant. The temperature of the skin of the premature infant, as well as that of the body, is affected directly by the surrounding temperature and, to a greater extent than it is in the normal infant.

Effects of Changes in Metabolism on Skin Temperature

Under constant environmental conditions, a simple linear relationship is found between the temperature of the big toes and the basal heat production per unit of surface area, and throughout the day, the temperature of the skin surface of the feet will change. Muscular exercise, which is known to affect metabolism, influences the temperature of the skin. This is observed during the first few minutes of exercise as the temperature of the skin falls, and when back at resting conditions, it rises back up.

Effects of Body Size on Skin Temperature

Skin temperature is a challenging parameter to predict due to the complex interaction of physical and physiological variations. One of these varying parameters is body size. Previous studies concerning the correlation of regional physiological characteristics and body composition showed that obese people have higher hand skin temperature compared to people of normal weight. Katic, Li, Kingma, and Zeiler (2017) showed that the skin temperature of the extremities (e.g., hands) is elevated in obese people in order to compensate for the lower heat loss in the body region. On the other hand, they showed that the abdomen area in obese people has lower skin temperature when compared to people of normal weight. These authors suggest that in order to model skin temperature of the hand and compare it with the experimental data, experiments have to establish clear input parameters of environmental conditions, physiological characteristics, and measured metabolic rate of all participants, from normal to obese. If a correlation to body size is part of the research goals, it is helpful to refer to standards of healthy weight. According to the World Health Organization, *normal* weight individuals are those considered to have body mass index (BMI) between 18.5 and 25.0 kg/m^2. *Overweight* individuals have a BMI from 25 to 30 kg/m^2 and individuals with the BMI higher than 30 kg/m^2 are considered *obese* (World Health Organization, 2016). All in all, a research study aiming at using body temperature as a measure of autonomic arousal during an experiment should take into consideration the participant's body size, using the parameters established by an international organization such as the World Health Organization.

Effects of Emotions on Skin Temperature

Finally, emotions will also influence the temperature of the surface of the skin. Studies with thermal infrared imaging have shown affective states like extreme *stress* (Pavlidis, Dowdall, Sun, Puri, Fei, & Garbey, 2007), *startle* (Shastri, Merla, Tsiamyrtzis, & Pavlidis, 2009), *fear* (Levine, Pavlidis, & Cooper, 2001), *arousal* (Nozawa & Tacano, 2009), and *happiness* (Nakanishi & Imai-Matsumura, 2008) are related to certain properties of facial skin temperature. For example, hyperemia (i.e., excess of blood in the vessels) of the face due to *excitement* causes a rise in the skin surface temperature over the cheeks. Studies that use laser Doppler flowmetry and photoplethysmography suggest that changes in microcirculation caused by subcutaneous vascular constrictions or dilation need to last for at least 5 seconds for decreases in temperature to take place (Kistler et al., 1998).

Two biological mechanisms enable thermal activation of affective causes: subcutaneous vasoconstriction and emotional sweating. Activated by epinephrine released in the blood stream, subcutaneous vasoconstriction is a response to threat that constricts the blood volume within veins under the skin (Pavlidis, Levine, & Baukol, 2001). This mechanism protects against excessive blood loss and possible hemorrhage in case of injury and is concentrated in the most exposed parts of the body (Vianna & Carrive, 2005). Once the threat has been removed, vascular relaxation is observed accompanied by a gradual temperature rise resulting from parasympathetic restoration (Nhan & Chau, 2010).

Emotional sweating is activated by norepinephrine binding on sympathetic preganglionic neurons that are situated on the spinal cord. This enables acetylcholine release in the synaptic cleft, which stimulates secretion at the sweat glands. This physiological phenomenon occurs mainly in specific body parts such as the palms, axillae, and soles of the feet. This increases elasticity and reduces friction of the skin in regions that have increased contact with the environment and external objects (Vetrugno, Liguori, Cortelli, & Montagna, 2003).

Changes in the surface temperature of the face are also related to the autonomic regulation of facial muscles. The facial muscles respond according to psychological and environmental factors (Nhan & Chau, 2010). Facial muscles, like all organs of the body, require nutrients supplied through the blood stream. Thus, adjustments in blood flow occur to cover muscular activity changing the emitted thermal print. For example, periorbital (Levine, Pavlidis, & Cooper, 2001) and supraorbital vessels (Puri et al., 2005) of the face have been observed to show heat escalations according to stressors that are believed to facilitate preparedness for rapid eye movement in fight or flight. During occasions such as these, a temperature dip on the cheeks is observed as the result of redirected blood to the eye musculature as well as of emotional sweating (Merla & Romani, 2007). The supraorbital and periorbital vessels feed the main muscles surrounding the eyes—the corrugator, procerus, and orbicularis oculi. Furthermore, the supraorbital regions have been postulated to represent prolonged periods of stress during mental engagement (Zhu, Tsiamyrtzis, & Pavlidis, 2007).

SKIN TEMPERATURE AND LANGUAGE RESEARCH

Research in applied linguistics and education can apply advancements in technology in bio-engineering and psychophysiology to measure emotional regulation and promote pro-social behavior of children in educational settings. For example, research in the areas of communication disabilities and speech-language pathologies may create the means to help impacted individuals to have meaningful interactions with others in their environment. A lot of research has made use of technology available on smartphones and tablets, which are loaded with educational and communication applications. Through these devices, not only verbal communication but body language, body movement, and emotions can be taught and explained, and meaningful exchange of nonverbal information can be achieved.

In addition, research in SLA has started to explore the benefits of making use of participants' (in this case, second-language learners) physiological data to improve the learning environment and outcomes. One application of such data has led to the creation of *context-aware* environments. Context-aware environments are those that are sensitive and responsive to the presence of people, that can read their body language, facial expressions, and body temperature without touching them, and through the interpretation of this data, they can provide an *ambient intelligent* response (as in biofeedback setups) with the goal of helping them feel more comfortable (Aarts, Harwig, & Schuurmans, 2001). Applying ambient intelligence in educational scenarios allows learners to be immersed in a digital environment that is aware of their presence and context, and which also suits their needs through personalization and adaptation of the learning environment to enable natural interactions that are anxiety-free (Santana-Mancilla et al., 2013). For example, a study conducted by Santos, Saneiro, Boticario, and Rodriguez-Sanchez (2016) explored the benefits of supporting second language learners affectively in a context-aware learning situation. Participants were told they were supposed to give a speech, and they were given one minute to prepare. During the entire experiment, participants' electrodermal activity and skin temperature were measured, a webcam registered their facial expressions and recorded their voice, and a video camera registered their body movements. According to the authors, their data suggested that participants were nervous during the planning and delivery of the speech, compared to a relaxation baseline. Their heart rate increased, their temperature increased, and their electrodermal activity increased. Therefore, considering the physiological changes detected, they explained that these changes were related to different affective states experienced by participants in the speech task that are known to cause higher levels of stress, anxiety, and nervousness; thus, such linguistic tasks when asked of second language learners should be accompanied by haptic, auditory, and visual relaxation suggestions.

Thermal infrared imaging is a strong candidate to monitor sympathetic activity in the autonomic system through changes on the skin temperature without having to place electrodes or physiological recorders on the participants. In recent years, infrared thermal imaging has been widely used in studies of emotions in facial expressions. When an emotion occurs, there is a change in facial temperature due to the blood flow that the body generates through blood vessels in the subcutaneous area. This skin temperature change can be qualified and quantified through infrared thermal imaging. For example, research focusing on the emotion of *joy* (i.e., when a subject is smiling) has found that the temperature of the nose and forehead decreases during the event (Nakanishi & Imai-Matsumura, 2008; Salazar-Lopez et al., 2015). A study conducted by Merla and Romani (2007) examined facial temperature changes during *stress*, *fear*, and *pleasure*, and they found that (1) discomfort of stress was paired with sweating especially around the mouth; (2) pain or fear lead to a decrease in facial temperature; and (3) arousal generated an increase in the temperature of the forehead, lips, and nose. Another study focused on the feeling of *guilt* in children, and they observed that overall facial temperature decreased, and the most visible change was on the tip of the nose (Ioannou et al., 2013). Another study, focusing instead on *fear*, studied participants who had been diagnosed with mild symptoms of post-traumatic stress disorder (PTSD) and compared the results with a control group. They found that the facial temperature in patients with PTSD was lower compared to those who in the control group (Di Giacinto et al., 2014). Finally, a study that used thermal imaging provided biomarkers for thermal images of the facial expressions that conveyed *joy*, *disgust*, *anger*, *fear*, and *sadness*. They selected regions of interest (ROIs) through image processing techniques that helped them establish a biomarker for each ROI (e.g., forehead, nose, cheeks, etc.). The purpose of establishing consistent biomarkers is to diagnose emotions through infrared thermal imaging. The study was able to successfully create a *smart* thermal system to diagnose emotions, and when tested on twenty-five subjects, it had an 89.9 percent success rate (Cruz-Albarran et al., 2017).

IMPORTANT CONSIDERATIONS ABOUT METHODOLOGICAL PROCEDURES

Skin temperature recorders measure the thermal response of the human skin. Variations in the skin temperature (SKT) mainly come from localized changes in blood flow caused by vascular resistance or arterial blood pressure. Local vascular resistance is modulated by smooth muscle tone, which is mediated by the sympathetic nervous system. For this reason, SKT variation reflects sympathetic activity and is another effective indicator of emotional arousal.

Accurate surface temperature reading can be obtained in three different ways: (1) using a temperature probe, (2) using a thermal imager, and (3) using an infrared thermometer. The former requires surface contact, and the latter two do not require contact with the surface in order to record its temperature.

Infrared radiation is a type of radiation that is invisible to the human eye, but we can feel it as heat. All objects that have temperature higher than absolute zero (0°Kelvin) emit infrared radiation. The hotter the object, the hotter the frequency of that radiation. Infrared temperature sensing devices detect the frequency of the infrared radiation from an object and convert that frequency reading into a temperature reading. There are two types of infrared temperature measurement devices that are widely available today: thermal imaging cameras, sometimes referred to as *thermal imagers*, and infrared thermometers, sometimes referred to as *IR guns*. Infrared thermometers can only read the temperature of a single point, whereas thermal imagers use a focal plane array sensor with pixel dimensions of 640 by 480 (640 x 480) and with each pixel acting as a sensing element, it gives the researcher over 300 thousand individual temperature points. So thermal cameras are the better alternative for research as they come with advanced optics, robust sensing, and recording packages.

A thermogram is the thermal image displayed by the camera of the object which is emitting, transmitting, or reflecting the infrared energy. Thermal imagers allow users to measure temperature in applications where conventional sensors cannot be employed, specifically in cases dealing with moving objects or where noncontact measurements are required. Thermal imagers provide an image that shows the temperature differences of the surface of the object being measured. Hot spots can be seen immediately on a thermal imager, unlike with traditional infrared guns, which only provide the average temperature of the area being measured.

Nowadays, noninvasive systems to monitor physiological changes have been booming. Infrared thermography (IRT) is a technology that uses infrared thermal cameras and allows measuring the radiation of energy that a body emits in a noninvasive way and without the limitations arising from the use of wired sensors. Therefore, the use of IRT has been increasing as a solution to physiological research.

Thermal infrared imaging, sometimes also called functional infrared thermal imaging (fITI), is considered an upcoming, promising methodology in the emotional research arena. Driven by sympathetic nerves, observations of affective nature derive from muscular activity subcutaneous blood flow as well as perspiration patterns in specific body parts. Thermal infrared imaging, by harnessing the body's naturally emitted thermal irradiation, enables cutaneous temperature recordings to be measured noninvasively, ecologically, and contact free. The autonomic nervous system (ANS) is at the forefront of biological heat displays, controlling unconscious heart rate, breathing, tissue metabolism, perspiration, respiration, and cutaneous blood perfusion, providing grounds for observations of emotional inference to be made. Thus, thermal infrared imaging (also referred to as functional infrared imaging, fITI) enables the characterization of the competing subdivisions of the ANS. Bioheat-based computations of thermal infrared signs have in the majority been based on participants' faces. This preference is attributed to the fact that the face is not obscured and is open to social communication and interaction.

Functional infrared thermal imaging has been adopted in a variety of studies involving human emotions as well as reflexes. In particular, it has been used to study *startle* response, *empathy*, *guilt*, *embarrassment*, *sexual arousal*, *stress*, *fear*, *anxiety*, *pain*, and *joy*.

To extract information of affective nature from variations of temperature on the surface of a subject's face, ROIs are used. These are regions on which most observations are based, such as the nose or nose tip, the periorbital and supraorbital vessels of the face, forehead, and the orbicularis oculi (surrounding the eyes), as well as the maxillary area or the upper lip (perinasal) (Ioannou et al., 2014). Regions on which fewer observations were gathered were the cheeks, carotid, eye, fingers, as well as the lips. According to the subject's response to the emotional stimulus as well as the ROI, temperature elevates or decreases (see table 5.1).

Standard Recording Devices

These are some of the options most widely used in standard research on sympathetic activity's influences on the regulation of emotional expression. There might be more current and better options in the market, so it is up to the reader to go with these devices or research the market for alternatives. The processing of thermograms is done externally using a computer with

Table 5.1 Overview of the Direction of Temperature Variation in the Considered Regions of Interest across Emotions

Emotions/ Regions	*Stress*	*Fear*	*Startle*	*Sexual Arousal*	*Anxiety*	*Joy*	*Pain*	*Guilt*
Nose	↓	↓		↑		↓		↓
Cheeks			↓					
Periorbital			↑	↑	↑			
Supraorbital			↑		↑			
Forehead	↓↑	↓		↑	↑		↓	
Maxillary	↓	↓	↓				↓	↓
Neck/carotid			↑					
Nose	↓							
Tail		↓					↓	
Fingers/palm		↓					↓	
Lips/mouth				↑				

Source: Table created by author.

a processor that meets at least the minimum requirements. Stimulants and visuals can be projected on a screen to study participants, in which case a projector is required. The first device is a thermal infrared imaging camera, the second device is a laser doppler blood flow monitor, the third and fourth devices are infrared thermometers, the fifth device is a contact measurement probe attached to a finger, and the last device is a contact temporal artery thermometer to be used on the forehead.

FLIR A310 Thermal Infrared Imaging Camera

FLIR (FLIR Systems) is one of the world leaders in thermal infrared imaging cameras. A FLIR camera commonly used in physiological research is the FLIR A310, which produces high-quality 76,800-pixel infrared images with embedded temperature readings. It also offers up to 8x digital zoom so that the researcher can pinpoint and monitor their exact target object. This camera has a thermal sensitivity of 0.05 at 30 °C, an infrared resolution of 320 × 240 pixels, and a spectral range between 7.5 and 13 µm. A study conducted by Cruz-Albarran et al. (2017) used a FLIR A310 camera. This camera was installed on a tripod at a height of 1.2 meters and at a distance of 1.2 meters from the study participant. This camera was calibrated based on Garcia-Ramirez et al.'s (2014) guidelines.

Periflux PF3, a Laser Doppler Blood Flow Monitor

The temperature of palmar finger skin can be measured with a Periflux PF3, which is laser Doppler flowmetry thermal imager (Periflux PF3, Perimed, Sweden). Laser Doppler signals can be transferred to a computer with Biopac's *AcqKnowledge* software (Biopac Systems, Inc.) for recording and analysis.

Diatek 9000, an Infrared Thermometer

The participant's hand temperature was measured with a Diatek 9000 infrared thermometer (Diatek, Inc., San Diego, California). The calibration accuracy of this infrared thermometer is ± 0.1°C in the range of 37°C to 39°C, and the measurement range of this instrument is 23.9°C to 42.2°C. The device consists of a grip for the hand and a holder and looks like a staple gun. When the scan button is pressed, the probe is activated to start reading infrared energy, which is converted into an electronic signal. This signal is then converted into a temperature, which is displayed in degrees Celsius. Before testing, the subjects were seated in the testing room for 15 minutes. The environmental temperature was 25 degrees Celsius. The subjects were asked to keep their hands at rest, to keep them at the same horizontal level, and not to touch cold or warm material, such as a cup of coffee. Measuring points were identified and marked on the dorsal and palmar aspects of both hands, at the level of the middle of the third metacarpal, away from visible veins. To facilitate measurement, the hands lay loosely on the table. The aspect of the hand to be measured was turned up, with the opposite side resting on the table. The probe was held perpendicular to and 1 centimeter from the surface of the hand. Measurements were taken at each location twice. If both readings were the same, that score was recorded. If the two readings were not equal, a third reading was taken. If the third reading was the same as one of the first two readings, then that score was recorded.

AccuSystem Genius 2 Infrared Thermometer

Tympanic temperature measurement devices like the AccuSystem (AccuSystem Genius 2 Tympanic Infrared Ear Thermometer, Covidien, Mechelen, Belgium) measure the amount of infrared heat produced by the tympanic membrane of the ear by means of a sensor probe. The tympanic membrane shares its blood supply with the hypothalamus, the thermoregulatory center of the human body. However, this necessitates appropriate application and access to the tympanic membrane. Consequently, the probe needs to be positioned in the auditory external duct in the appropriate angle to the tympanic membrane.

Biopac's SKT100B Amplifier with a TSD202 Fast Response Thermistor on the Fingertip

Biopac's (Biopac Systems, Inc.) SKT100C measures surface, core, or air temperature, and along with a TSD202 series temperature probe, they can record temperature changes to 0.0001°C resolution. Front panel controls allow selection for either absolute or relative temperature measurements. The SKT100C operating temperature range is 40°F to 140°F (5°C to 60°C). Use the AcqKnowledge software to calibrate the SKT100C's output in °F or °C. When using Biopac's setup, SKT is usually measured from the fingertip on the first joint of the nondominant ring finger.

Exergen Temporal Artery Scanner

In temporal artery scan measurements using the Exergen scanner (Exergen Corp, Watertown, Massachusetts), temperature is registered by slow scanning the participant's forehead in the temporal artery region and behind the ear by direct skin contact. The thermometer measures the naturally emitted infrared heat form the temporal arterial supply.

Recommendations for Data Collection

The following are suggested protocols for data collection, as typically seen in the psychophysiology literature.

Recording Conditions

Cutaneous thermal responses to external stimuli of psychophysiological valence could result in small temperature variations of the ROI. Thus, it is extremely important to ensure that the observed temperature variations are not artifacts due to either environmental physiological causes or simply subject motion. As for the environment, a crucial role is played by the experimental room or setup in which measurements take place. The environmental temperature has to be steady throughout the experimental session. No direct ventilation should hit the subject. In addition, if possible, room temperature and relative humidity should be set at comfortable values (i.e., thermoneutrality) for the subject. For example, in Western countries these values are usually set at approximately 22–24°C and 50–60%, respectively (Merla & Romani, 2006). Several technical solutions are available in this perspective, all of them capitalizing on the continuous monitoring of the environmental conditions (Gane et al., 2011).

Other issues that should be taken into consideration during the experimental setup are the prevalence or absence of systemic sources of thermal noise. These include thermal reflective walls, furniture material, direct sunlight through windows, and heat-emitting monitors in close proximity to the participant's face. These will result in overestimation or underestimation of the physiological temperature changes in the given ROIs. Prior to the initiation of the study, the participant or subject (along with the experimenter) should be left to acclimatize in the room for 10–20 minutes. This enables the restoration of cardiovascular and respiratory activity, as well as allows skin temperature to reach a thermal equilibrium with the experimental room. Some authors suggest the removal of corrective eyewear prior to the experimental session because glass is opaque to infrared light. Once removed, enough time should be provided to allow pressure-related temperature restoration of the surrounding tissue of the nose (Gane et al., 2012). During recordings, the distance between the camera and the subject depends on the size of the ROIs to be imaged and the camera's optics. Usually, the camera is placed anywhere between 30 and 70 centimeters from the participant (Kuraoka & Nakamura, 2011) to 1–3 meters away (Nakanishi & Imai-Matsumura, 2008).

Exclusion Criteria

Exclusion criteria for participation in a fITI study should include aspects related to normal cutaneous thermoregulation, such as peripheral neuropathy, micro- and macroangiopathies, connective tissue diseases, and psychophysiological disorders. Requirements for participation include the abstinence from intake or consumption of vasoactive substances (nicotine, caffeine, alcohol) for at least 2–3 hours prior to participation in order to improve reliability of the assessments (Merla & Romani, 2006).

Circadian Rhythm

Finally, it is important to take into consideration the circadian rhythm of the human body when conducting an experiment. Recordings should take place for the majority of participants at the same time and season in order to have consistent group comparisons and to be able to observe temperature variations on the same scale. It has been illustrated that skin temperature varies throughout the day. Whereas in the evening the core body temperature and proximal skin temperature rise in contrast to distal skin temperature, the opposite effect seems to take place in the morning (Kräuchi & Wirz-Justice, 1994). Furthermore, since heat exchange with the environment occurs by "means of conduction, convection, radiation and evaporation" (Kräuchi & Wirz-Justice, 1994, p. 148), different homeostatic mechanisms take place during the different seasons of the year. For example, sweating and increased blood flow followed by peripheral blood vessel constriction is observed in warm seasons, whereas the opposite happens in cold climatic conditions. This phenomenon occurs mainly in distal skin regions such as the fingers, nose, toes, and ears through smooth muscles in arterioles and arteriovenous anastomoses (Hales, 1985).

Establishing Baselines

In order to interpret observations after the experiment, it is necessary to select an appropriate baseline for each participant (Levenson, 1988). Establishing an autonomic starting point is the foundation for the interpretation of the physiological changes observed during the experiment. So, for example, if a particular emotion, such as *fear*, is assumed to cause an increase in supraorbital and periorbital temperature, then an appropriate baseline condition would serve as an actual comparison with the experimental condition.

The use of a resting baseline provides grounds for experimental comparisons. To achieve that, the experimenter should ask participants to "rest and empty their minds of all thoughts, feelings, and memories" (Levenson, 1988, p. 24). Using rest as a baseline gives the researcher an adequate contrast measurement since during rest the parasympathetic nervous system is active, being less likely to represent an emotional response.

Opposing or near opposing emotions to the experimental condition could also serve as appropriate baselines. For example, if *happiness* is the emotion of interest, then appropriate baselines would be *sadness*, *anger*, and even *fear*. This comparison is based on the fact that *happiness*, although a positive emotion, is characterized by an increase in heart rate as a result of vagal withdrawal; however, it differs from negative emotions in terms of peripheral vasodilation (Kreibig, 2010, p. 23).

Not examining physiological changes from a reference baseline point has two main drawbacks. First, no baseline means no directionality description for the target emotion. Second, if an individual is subjected to two different emotional conditions and does not provide measurable autonomic signs in one of the two, then no matter how good the results of the other condition are, no contrast between the two emotions can be performed.

No gold standard exists for choosing an appropriate baseline. However, different types of baselines have been used across thermal imaging studies, and in certain cases they could be easily applied in studies with similar design. Kreibig (2010) provides a review of autonomic reactions during positive and negative emotional states, which should be used as a guide for choosing an appropriate reference baseline point.

Recommendations for Data Processing

Signal Analysis

After data collection, a number of post-processing steps on the data should be performed. For example, data files retrieved from thermal sensors must be examined in order to reduce signal-to-noise ratios (Jung, Jazizadeh, & Diller, 2019). For example, to reduce the noise in the signal, the researcher can use the Savitzky-Golay filter, which is a digital filter that can be applied to a set of digital data points for the purpose of smoothing the data, that is, to increase the precision of the data without distorting the signal tendency.

Statistical Analysis

The post-processed data then will be ready for statistical analyses. In designing statistical analyses for their data, investigators should decide what is appropriate based on the nature of the data and goal of the study.

Chapter 6

Electroencephalography

A BRIEF OVERVIEW OF ELECTROENCEPHALOGRAPHY

An electroencephalogram (EEG) is a test used to evaluate the electrical activity in the brain. While EEG technology has been around for the better part of the last century, it was only fairly recently that clinicians and expert neuroscientific researchers were able to set up and analyze recordings under strictly controlled laboratory conditions with electrode caps containing 64 channels or more (an electrode capturing brainwave activity is called an EEG channel; typical EEG systems can have as few as a single channel to as many as 512 channels). These high-density electrodes (see figure 6.1) evenly spaced across the human scalp are used to help researchers discover the underlying neural mechanisms involved in actions, cognition, or emotional processing.

EEG measures electrical activity (in voltage) generated by the synchronized activity of groups of neurons; it provides excellent time resolution, allowing the experimenter to analyze which brain areas are active at a certain time at millisecond timescales. Recent advancements in computer hardware and processor technology have enabled researchers all around the globe to vastly expand the existing knowledge about the complexity of the human brain and gain deeper insights into brain processes and structures.

The brain consists of approximately 86 billion neurons (which is an estimate as there has not been an official count yet), densely interconnected via synapses, which act as gateways of excitatory (i.e., synapses propagate information across neurons) or inhibitory (i.e., prevent the passage of information from one neuron to the next) activity. Any synaptic activity generates a subtle electrical impulse referred to as post-synaptic potential. The burst of a single neuron is too small to be noticed; however, whenever a smaller group of neurons (about 1,000 or more) fires in synchrony, they generate an electrical

Figure 6.1 EEG Headcap for Wireless EEG Measurement. This Study Participant Is Wearing an EEG Headcap for Wireless EEG Measurement and Recording for Mobile Applications (by Enobio EEG Systems). *Source*: Image courtesy of iMotions, Inc.

field which is strong enough to spread through tissue, bone, and skull. When this happens, it can be measured on the head surface.

Event-Related Potentials (ERPs)

By recording small potential changes in the EEG signal immediately after the presentation of a sensory, cognitive, or motor stimulus, it is possible to record specific brain responses to the investigated event. This change in the EEG signal is called ERPs. In other words, it is the stereotyped electrophysiological response to a stimulus.

ERPs have attracted a great deal of interest because they may convey information about the dynamics of cognitive processing by the brain. Temporal variation of the ERP occurs on a millisecond time scale, which is conducive to measurement of the rapidly changing dynamics of cognition. Thus, a recurring theme in the ERP literature is the identification of components spanning brief periods of time before or after a measurable event, and the classification of these components pertains to sensory, motor, or higher-order cognitive processes of the brain.

Researchers have shown that sampling EEG on the scalp with a dense array of more than 64 electrodes and solving the “inverse problem of EEG” using EEG source imaging (ESI) techniques (analytic methods and head models that project the scalp voltages back to the cortex) can reliably monitor the spatial and temporal changes in brain activity. In most laboratories, ESI is accomplished with a head geodesic system containing 64 or 128 electrodes. Most commercially available dense array head nets are equipped with 64, 128, or 256 electrodes.

For years, researchers have shown that information is lost unless an interelectrode distance of 1 to 2 centimeters is achieved with EEG sampling. Achieving 1 to 2 centimeter sampling density requires 500 electrodes on average distributed evenly over the surface of an average-sized adult head (human head size is so variable). However, researchers have also shown that spatial sampling obtained with 256 electrodes or 128 electrodes is more than adequate for most purposes. In addition, using too many electrodes has some disadvantages: more electrodes means greater opportunity for both biological artifacts, such as eye and body movements, and nonbiological artifacts, such as electromagnetic interference and salt bridges; the shorter the interelectrode distance the more likely electrolyte spreading (often referred to as a "salt bridge"); small interelectrode distances are optimal only for highly localized signal sources that are close to the surface, whereas signals from deeper and spatially extended generators may cause phase cancellation; and the higher the spatial and temporal sampling rate, the more data will be acquired, the more data must be crunched, the more you'll need faster CPU, faster memory chips, larger storage media, and the greater the expense.

While most peripheral sensors measure body signals that are modulated by cortical processes, direct brain recordings provide access to the electric processes underlying human cognition and behavior. EEG electrodes can be mounted in flexible caps, and they record the electrical voltage distribution across the scalp, which is considered to be generated by neural synchronization inside of cortex, which results in electric fields that are propagated toward the surface.

Recent progress in online signal decontamination and feature extraction allows for real-time computation of several core metrics such as cognitive workload or engagement based on the recorded EEG raw data. While advanced systems allow for customized adjustment and individualization of the transformation matrices from raw data to metrics, several EEG devices even provide pre-calculated metrics without further adjustment, allowing the experimenter to jump straight into data collection.

ELECTROENCEPHALOGRAPHY AND LANGUAGE RESEARCH

Talking is a daily routine in our lives. The large number of published papers measuring overt speech responses using EEG clearly indicates that there is an interest and a great demand for research in language processing and language production combining overt speech responses with EEG recordings. However, when using electroencephalography (EEG) recordings, it is hard to parse out signals that correlate only with language production due to the fact that muscle activation of the lips, head, and eye movements that accompany overt speech might distort the EEG signal, making it very hard to investigate language production using EEG. To avoid this problem, some language production studies focused on meta-linguistic tasks, covert naming, and delayed naming (Ganushchak, Christoffels, & Schiller, 2011). These tasks are successful in avoiding potential speech movement–related artifacts, but they are also limited. For instance, in case of covert naming, it is not possible to ascertain whether participants followed task instructions. Or, in the case of error processing, it cannot be completely excluded that some of the observed errors were due to action slips (e.g., participant responded to a command with the wrong hand) and were not necessarily linguistic errors. These are a few of the challenges that research on language processing and use might face when using EEG methods.

Speech is the most common means of communication used by humans, which leads to the fact that we are inherently capable of distinguishing between sounds from familiar and unfamiliar languages when we listen to them. EEG studies have also focused on the brain representations in second language learning. For example, a study conducted by Soman et al. (2019) attempted to describe the key differences in the neural representations when a person is presented with speech signals of a known and an unknown language and to capture the evolution of neural responses in the brain for a language learning task. They used EEG signals participants listened to a given set of words from English (familiar language) and Japanese (unfamiliar language). The subjects also provided behavioral signals in the form of spoken audio for each input audio stimuli. In order to quantify the representation level differences for the auditory stimuli of two languages, they used a classification approach to discriminate the two languages from the EEG signal recorded during listening phase by designing an off-line classifier. This study revealed that the time-frequency features along with phase contain significant language discriminative information. The language discrimination was further confirmed with a second subsequent experiment involving Hindi (the native language of the subjects) and Japanese (unknown language). A detailed analysis was performed on the recorded EEG signals and the audio signals to further understand the language learning processes. A pronunciation rating technique on the spoken audio data confirmed the improvement of pronunciation over the course of trials for the Japanese language. Using single-trial analysis, they found that the EEG representations also attained a level of consistency indicating a pattern formation. The brain regions responsible for language discrimination and learning identified based on EEG channel locations were found to be predominantly in the frontal region.

Other EEG studies have focused on the production of a single word. According to the Levelt et al. (1999), production of a spoken word consists of lexical selection, lemma retrieval, morphological and phonological code retrieval, and articulation. Most of the recent ERP studies focused on the lexical access aspect of word production. For example, Eulitz et al. (2000) mapped the time course of phonological encoding during overt picture naming and forming nominal phrases (e.g., using the name and the color of the picture. These authors compared overt production with passive viewing of the same pictures, and they found ERP markers of phonological encoding between 275 and 400 milliseconds after picture onset. This effect was more pronounced in middle and posterior temporal regions in the left than the right hemisphere, possibly suggesting the involvement of Wernicke's area during phonological encoding.

A little more challenging is the study of conceptual planning in complex utterances in overt language production. Habets et al. (2008) addressed the so-called linearization problem, which is the ordering of events in a sentence (e.g., "before X did A, Y did B" or "after Y did B, X did A"). In this study, participants were shown a sequence of two pictures. Each picture consisted of an object that has a strong association with a particular action, like *book* and *reading*. Participants were instructed to describe the sequence of two actions associated with the object in chronological/reverse order. A color cue indicated a to-be produced order. ERPs for the "after" condition were more negative than for the "before" condition. This difference emerged between 180 and 230 milliseconds after the vocalization cue, and had a fronto-central distribution. The timing of this effect corresponds closely with comprehension studies investigating temporal order of events in sentences and is associated with the engagement of working memory processes in understanding more non-chronological sentences.

Some researchers have been interested in lexical access during language production in a second language. To attain such goal, researchers focus on cognate words (Strijkers et al., 2010). Cognates are words that are phonologically similar in different languages (e.g., the English–Portuguese pair: *agent–agente*). In EEG studies, cognates are typically named faster than non-cognates. For example, Christoffels et al. (2007) found more negative amplitudes for cognates compared to non-cognates at about 300 milliseconds after the picture onset, which corresponds with the phonological encoding of words. Strijkers et al. (2010) found a somewhat earlier effect of cognates starting around 200 milliseconds after picture onset, with cognates having more negative amplitudes than non-cognates. The pattern was remarkably similar during both first and second language naming.

Another target area at the intersection of second language production and EEG research investigate the role of cognitive control and inhibition during language switching. To investigate this issue, Chauncey et al. (2009) used a switching paradigm, where participants on a given cue were required to name a picture in their first (L1) or second language (L2). The authors found that naming in L1 was slower and the ERPs were modulated between 275 and 375 ms (time window of N2) compared to naming pictures in L2. The authors also found modulation of the N2 amplitudes. Participants were instructed to overtly name pictures in their L1 (English) and their L2 (French). Pictures were preceded by a word prime, presented for 70 milliseconds. Primes were either the (English or French) name of the to-be named picture or were unrelated to the picture. The language of the prime word affected ERP at about 200 milliseconds after picture onset, but only when pictures were named in L2 and not in L1. The authors argued that the L1 prime interfered with suppression of the L1 lexical activation, which is needed for L2 but not L1 production, thereby creating a conflict reflected in the N2 amplitudes.

Other researchers were interested in the processes involved in translation from one language to another. For example, Christoffels et al. (2011) asked participants to translate interlingual homographs (i.e., words that shared orthographic form but had a different meaning in two languages and control words. Participants were asked to translate targets from and to their first and second language. The authors showed that the brain starts to distinguish between translation directions as early as 200 milliseconds. The results of the study are in line with the idea that language information in the input, serving as a "language cue," rather than the output lexicon, helps to reduce competition between languages when selecting the proper target response.

Finally, research focusing on mindfulness awareness using EEG recordings can be extremely helpful in elucidating the benefits of mindfulness awareness on learning and general well-being. For example, a study conducted by Siripornpanich et al. (2018) used 53 typically developing children participants (27 girls, 26 boys), all in the sixth grade, ages ranging from 11 to 12. Participants belonged to two different schools, one of which uses a mindful-based education (Mind-Edu) approach in their school curriculum, whereas the other adopts only the country's core curriculum. Believing that Mind-Edu could have traceable effects on resting state brain activities of the school-aged students in the former school, Siripornpanich et al. (2018) compared the EEG power spectrum of both groups. Although their results showed no significant difference between the groups on the mean value of absolute beta, alpha, and delta powers over all electrode sites, the Mind-Edu group had a significantly lower absolute theta power over the posterior brain regions and a significant smaller theta/beta ratio over the Cz electrode. The authors argue that these results suggest that implementation of Mind-Edu into the regular elementary school curriculum would be beneficial for enhancing maturation in brain areas involved with cognitive control and self-regulation. Mindfulness-based education has increasingly been recognized as an effective educational approach to promote the social and emotional competence of both children and adults.

IMPORTANT CONSIDERATIONS ABOUT METHODOLOGICAL PROCEDURES

With so many options to choose from, the researcher must select an EEG recorder based on their research goal. An electrode capturing brainwave activity is called an EEG channel, and typical EEG systems can have as few as a single channel to as many as 256 channels. Price differences in EEG systems are typically due to the number of electrodes, among other factors. There are several purposes for using larger electrode arrays (dense array EEG) that include (1) adequate spatial sampling as biophysical analyses have shown that information is lost unless an inter-sensor distance of 1 to 2 centimeters is achieved with EEG sampling; and (2) detecting clinical signals, which is required not only to localize brain pathology, such as an epileptic spike, but to detect it. Another advantage of using multichannel EEG systems is that they prevent the loss of potentially crucial data caused by when electrode distances grow further apart when fewer are deployed.

Other factors that affect the price of an EEG recorder are the quality of the digitization, the quality of the amplifier, and the number of snapshots the device can take per second (this is the sampling rate in Hz). EEG is one of the fastest imaging techniques available as it can take thousands of snapshots per second (256 Hz or higher). Current systems display the data as continuous flow of voltages on a screen.

Standard Recording Devices

There is a good number of manufacturers who now produce reasonably affordable EEG recording equipment. Before selecting a recording device for their experiment, researchers should consider consulting peer-reviewed articles for reliability and validation information of that particular recording instruments. Other considerations would be the number of electrodes each device offers, easy-to-use software for data manipulation, technical support, and cost. Considering the first criterion, reliability, and validation of such devices through the publication of study results on peer-reviewed journals, here is a list of devices that are more widely cited[1]: Compumedics NeuroScan, Brain Products, BioSemi, Electrical Geodesic Incorporated, Advanced Brain

Monitoring, Emotiv, NeuroSky, g.tec, ANT Neuro, Neuroelectrics, Muse, Open BCI, Cognionics, MBrainTrain, Enobio (figure 6.1), and B-Alert X10.

Recommendations for Data Collection

The advancement of knowledge in any field of research requires that data be collected and reported by observing standardized protocols. The progress of a field depends on data that are recorded reliably, analyzed properly, and interpreted with cautious creativity. A researcher must pay attention to several important details, from the design of an experiment to the analysis and report of the result, so that all details are documented sufficiently, allowing others to replicate the results. Additionally, the data must be measured correctly and analyzed carefully to distinguish meaningful information from noise. In a committee report commissioned by the Society for Psychophysiological Research and published in 2000 by the *Psychophysiology* journal, Picton et al. offer a very detailed and comprehensive list of guidelines for data collection and reporting protocols intended for research on ERPs, but that still apply to research in other psychophysiological measurements. A very brief summary of some areas in this report is found below (see Picton et al., 2000 for more information):

Study Design

Research experiments must be designed so that the measurements will test one explanation and rule out others. Picton et al. (2000) published general guidelines that can be very helpful for any experimenter who plans on using EEG data in their study. They suggested the following steps for the formulation of a study: (i) the study rationale must be clearly presented; (ii) the experiment's hypothesis should be clearly stated; (iii) tasks should be designed carefully so that they elicit the cognitive processes being studied; (iv) the participant's behavior during the experiment should also be taken into account; (v) strategies used by participant should be controlled by clear instructions and design, and should be evaluated by debriefing the subject; and (vi) the sequencing of the experimental conditions must be stated and controlled (pp. 128–130).

Subjects

When it comes to selecting and welcoming participants, the following guidelines are given by Picton et al. (2000): (i) first, informed consent must be read, signed, and stored safely; (ii) the total number of subjects in each experiment must be given and population sampling procedure explained, when applicable; (iii) the age range groups of the study participants must be provided; (iv) the participants' gender must also be reported, (v) required sensory and motor abilities matching the stimuli for the experiment should be asked and reported; (vi) the participant's cognitive ability relevant to the task at hand should be described; (vii) participants should be selected based on clear diagnostic criteria, and sample groups should be made as homogenous as possible; (viii) all possible medications used by participants should be documented, and some might even be considered as part of the exclusion criteria, given that they may affect the outcomes; and (ix) a control group must be included in the experiment, and their characteristics must differ from the experimental subjects only on the parameters under investigation (pp. 130–132).

Stimuli and Responses

Some guidelines are also required for the design of stimuli and responses. Based on Picton et al.'s (2000) guidelines, the following are some of the most important considerations to bear in mind: (i) the stimuli and instrumentation used in the setup of the study so that it can be replicated by another experimenter; (ii) the precise timing of a stimulus and each step and task must be described; (iii) the experimenter must keep in mind what cognitive processes will be examined when selecting stimuli, and they should also be reported; and (iv) and all relevant verbal and nonverbal responses made by participants should be described when reporting the study (p. 132).

Electrodes

When deciding on the physiological recording desired for a study based on the outcomes required to investigate phenomena of the emotional or cognitive arena, choosing the correct device to elicit that information is imperative. It is also crucial to select appropriate electrodes, gels, and other disposable and non-disposable supplies. How they were used is sometimes relevant for the interpretation of the results, and they should be reported as well. For example, when electrodes are used for the recording of physiological data, the gain or resolution of the recording system, the filtering characteristics of the recording system, and the rate of analogue to digital conversion must be specified (Picton, 2000, p. 135).

Electrode Placement on the Head

Electrode placement on the head adheres to a formal standard called the 10/20 system or the *International 10/20 system* (see figure 6.2). This system uses the distance from the bridge of the nose (the *nasion*; see figure 6.2) to

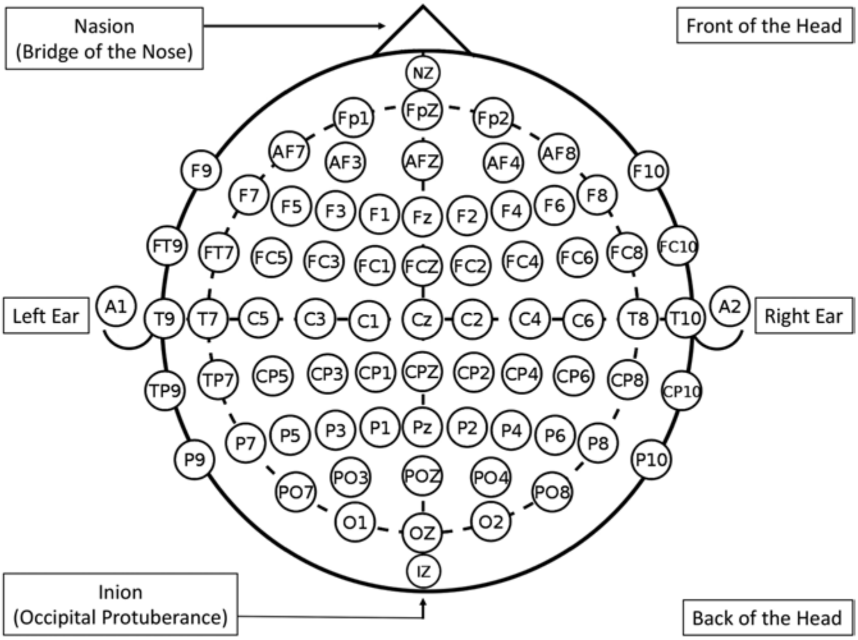

Figure 6.2 Electrode Placement on the Head Following the International 10/20 System. *Source*: Diagram created by author.

the lowest point of the skull from the back of the head (the *inion*, see figure 6.2) as a reference distance for a given person's head size. The electrodes are then separated from each other either by 10% or 20% of this reference distance (first diagram). When greater resolution (what we call granularity) is required, the 10/20 system (see figure 6.2) is extended where now the electrodes are separated by 10% of the reference distance (10/10). This is called the MCN system. Further resolution of 5% separation (10/5) distances adds even more electrodes to the network cluster. Since the voltage fluctuations measured at the electrodes are very small, the recorded data is digitized and sent to an amplifier. The amplified data can then be displayed as a sequence of voltage values.

Various parts of the brain serve different functions, so placement systems like the 10/20 system attempt to standardize the exact positioning of each electrode (and assign symbols to each location such as Cz or P3) to access brainwave data at a specific brain location that serves a specific brain function(s). Each electrode placement site has a letter to identify the lobe or area of the brain it is reading from: pre-frontal (Pf), frontal (F), temporal (T), parietal (P), occipital (O), and central (C). There are also (Z) sites, and a

"Z" (i.e., zero) refers to an electrode placed on the midline saggital plane of the skull (FpZ, Fz, Cz, Oz) and is present mostly for reference/measurement points. These electrodes will not necessarily reflect or amplify lateral hemispheric cortical activity as they are placed over the corpus callosum, and do not represent either hemisphere adequately. Even numbered electrodes (2, 4, 6, 8) refer to electrode placement on the right side of the head, whereas odd numbers (1, 3, 5, 7) refer to those on the left.

For example, placements Fp1, Fpz, and Fp2 collect important pre-frontal cortex data which acts as an "executive" for the decision-making process, weaving past events to present experiences in order to make the best choices. Placements at F7, F6, F5, and so on capture frontal lobe data associated with the choice of good and bad decisions, the suppression of socially unacceptable responses, and determining similarities and differences between events and things.

Recommendations for Data Processing

Signal Analysis

The number of responses that need to be averaged will depend on the measurements being taken and the level of background noise present in single-trial recordings. The noise should be assessed in the frequency band in which the component is measured. In addition, all digital filtering algorithms used in the experiment needs to be specified. And most importantly, artifacts must be located and eliminated in order to improve the quality of the data, and the steps taken to eliminate them must be documented. One way to do that is to inform participants if there is anything they can do to reduce the number of artifacts in the recording, as long as it does not affect their behavior to the extent that it would affect the data.

Statistical Analysis

In designing statistical analyses for their data, investigators should not feel bound by one specific or commonly used statistical method. The statistical analyses must be appropriate for the nature of the data and goal of the study. Several kinds of analyses that use repeated measures require appropriate corrections before the data can be manipulated. Another important consideration to bear in mind is that the absence of a statistically significant difference does not mean that the responses are the same. Unfortunately, few statistical tests can prove significant similarities. Comparisons between groups should not be limited to one measurement only, should use appropriate statistics to assess the gourds and the individuals within the group in order to account for differences in variability between the groups. Another aspect of the data that is statistical in nature is that single-case studies need properly matched control subjects, and the reliability and reproducibility of the data from one participant must be demonstrable (Picton, 2000).

Interpreting EEG Data

The cerebral cortex is the outer layer of neural tissue and it is responsible for higher thought processes including speech and decision-making. The cortex is divided into four different cortices: the frontal, parietal, temporal, and occipital.

The Occipital Cortex: This cortex is primarily responsible for processing visual information. EEG experiments with visual stimuli (videos, images) focus on effects in occipital regions.

The Parietal Cortex: This cortex is primarily responsible for fusing various bodily reference frames (eye-centered, head-centered, hand-centered, body-centered). Also, parietal cortex is active during self-referential tasks—when individuals are encountering objects or information that is important to them, for example.

The Temporal Cortex: The Temporal Cortex has lateral aspects which are responsible for language processing and speech production. Medial (i.e., *inner*) regions are more active during spatial navigation. The hippocampus is located here, and it is where individuals form spatial and autobiographical memories from early childhood days, for example.

The Frontal Cortex: This cortex is located in the front part of the human brain, is enlarged compared to other mammals. The frontal cortex is related to cognitive control. It keeps individuals from getting into risky situations and binds various memories and experiences into a consistent conglomerate.

Each part of the cortex is responsible for processing different types of sensory information. EEG monitors the time course of electrical activity generated by the brain, so the experimenter can interpret which brain areas are responsible for processing information at a given time.

Apart from the regional characteristics of where certain electrical activity originates, it is also possible to analyze which frequencies primarily drive the ongoing activity (see Abhang, Gawali, & Mehrotra, 2016). Whenever the brain is in a certain state, the frequency patterns change (see table 6.1).

Finally, as a rule of thumb, new findings should always be contrasted to those in the literature. The extent (or limitations) of the generalizability of the results is usually described. Then the experimenter should discuss any unexpected findings that were not predicted in the research hypothesis before ending with relevant implications of the results and areas that will require further experiments and investigation.

Table 6.1 ***The Five Types of Brain Waves***

Frequency Band	*Frequency Range*	*Brain States*
Delta Waves	0.5–4 Hz	In sleep labs, delta waves are examined to assess the depth of sleep. The stronger the delta rhythm, the deeper the sleep. Interestingly, delta waves are only present in non-REM phases, when an individual is not dreaming, for example.
Theta Waves	4–8 Hz	Theta is associated with a wide range of cognitive processing such as memory encoding and retrieval as well as cognitive workload. Whenever one is confronted with difficult tasks (counting backwards from 100 in steps of 7, or when recalling the way home from work, for example), theta waves become more prominent.
Alpha Waves	8–12 Hz	Whenever individuals close their eyes and bring themselves into a relaxed, wakeful state, alpha waves take over. Alpha is reduced with open eyes and drowsiness. Therefore, alpha coordinates multisensory processing, attention, and concentration. Biofeedback training often uses alpha waves to monitor relaxation.
Beta Waves	12–35 Hz	Over motor regions, beta frequencies become stronger as a person plans or executes movements of any body part. Interestingly, this increase in beta is also noticeable as we observe bodily movements of other people. The brain seemingly mimics their limb movements, indicating that there is an intricate "mirror neuron system" which is coordinated by beta frequencies.
Gamma Waves	>35 Hz, typically 40 Hz	Gamma frequencies are a less understood area of EEG research. Some researchers argue that gamma reflects attentive focusing and serves as carrier frequency to facilitate data exchange between brain regions. Others associate gamma with rapid eye movements, so-called micro-saccades, which are considered integral parts for sensory processing and information uptake.

Source: Table created by author.

NOTE

1. For more information on EEG recording devices and procedures, consult iMotions' Pocket Guide on EEG, retrievable from https://imotions.com/guides/electroencephalography-eeg/

Chapter 7

Functional Magnetic Resonance Imaging

A BRIEF OVERVIEW OF FUNCTIONAL RESONANCE IMAGING

Functional magnetic resonance imaging or functional MRI (fMRI) measures brain activity by detecting changes associated with blood flow. This technique relies on the fact that cerebral blood flow and neuronal activation are coupled. This means that when an area of the brain is in use, blood flows to that region. Functional brain mapping with magnetic resonance imaging works by detecting regional changes in cerebral metabolism, that is, blood flow volume or oxygenation in response to task activation. The most popular technique utilizes blood oxygenation level dependent (BOLD) contrast, which is based on the differing magnetic properties of oxygenated (diamagnetic) and deoxygenated (paramagnetic) blood. These magnetic susceptibility differences lead to small but detectable changes in susceptibility-weighted magnetic resonance image intensity. However, relatively low image signal-to-noise ratio of the BOLD effect, head movement, and undesired physiological sources of variability (cardiac, pulmonary) make detection of the activation-related signal changes difficult. Fortunately, rapid image acquisition techniques can be used to generate data sets with hundreds of images for each slice location that can be statistically analyzed to determine the foci of brain activity.

fMRI has become the most popular method for assessing functional brain topography for both research and clinical purposes; for example, it may be used to determine which parts of the brain are handling linguistic tasks. Neuroscientists are always looking for ways to decode a person’s conscious experience based on noninvasive measurements of brain activities. Neurologists are interested in examining the different functions of certain parts of the brain, whereas a psychologist may be interested in examining where in the brain things like *cognitive control* takes place (D'Esposito, 2010). fMRI measurements can provide insight into a person's cognitive processes while performing linguistics tasks, such as reading, word retrieval, speech comprehension, translating between languages, premedical phonemic processes, semantic processing of spoken words, sentence comprehension, semantic and syntactic constraints, prosody and speech interpretation, comparing images, articulation (during speech), monitoring speech output, and so on.

Despite these exciting prospects, some fMRI studies have been criticized due to the difficulty in reproducing their experimental conditions, in generalizing their findings, or allowing for statistical analyses, as these studies are often case studies or based on small samples (Vul et al., 2009). Some of the other arguments underlying such criticism are due to the fact that fMRIs only measure the secondary physiological correlates of neural activity, so it is not a direct measure. Despite the fact that fMRI measurements do not provide a direct measure of neural activity, they still bring us a step closer to understanding what is happening in the brain, compared to other behavioral correlates that physiological research has traditionally depended on. Therefore, although currently considered to be a qualitative measurement tool, fMRIs are a much more objective measure of a person's mental state than a self-report questionnaire will ever be, as the latter is often very subjective. The relationship between the fMRI signal and the underlying activity is a promising area of psychophysiological research, and a variety of techniques have been developed to calibrate an individual's response to a task or prompt in order to obtain a more quantitative measure of neural activity.

How Functional Magnetic Resonance Imaging Works

Electricity is the language of the brain. At any moment, there are millions of small electrical impulses, also known as action potentials, happening in the brain. At synaptic junctions, these impulses release specific chemicals (i.e., neurotransmitters), which in turn modulate the electrical activity in the next cell. This is the fundamental basis for neural communication. These processes underlie all thoughts, feelings, and actions, and a neuroscientist's main goal is to understand how the observed electric events correlate with them.

However, fMRI does not exactly directly measure electrical activity (like EEGs or MEGs) but rather it measures the indirect consequences of neural activity, which is the hemodynamic (i.e., blood flow) response. In principle, this is not different from the concept behind a classic thermometer. Thermometers do not directly measure temperature, but rather the volume of mercury in a narrow glass tube. It is the mercury that increases or decreases in volume based on the external temperature, and those volume changes are translated into readings of the external temperature. Because these two parameters are tightly coupled and standardized, a well-calibrated thermometer can properly track the temperature. But this concept is less effective if an observed coupling is incomplete, noisy, or just very complex. For example, certain types of neuronal activity are effectively invisible to fMRI scans, resulting in systematic biases. The extent to which coupling depends on unknown variability limits the extent to which it is possible to correctly interpret the BOLD signal. The pathway from neural activity to the fMRI BOLD response is schematized in figure 7.1.

fMRIs measurements are limited to the neural activity that is systematically associated with changes in the relative concentration of oxygen in local blood supply. Because oxygenated blood has different magnetic susceptibility relative to deoxygenated blood, changes in the ratio of oxygenated/deoxygenated blood (which is also known as the *hemodynamic-response function*) can be inferred with fMRI by measuring the BOLD response.

Oxygen is delivered to neurons by hemoglobin in capillary red blood cells. When neuronal activity increases there is an increased demand for oxygen, and the local response is an increase in blood flow to regions of increased neural activity. Hemoglobin is diamagnetic when oxygenated but

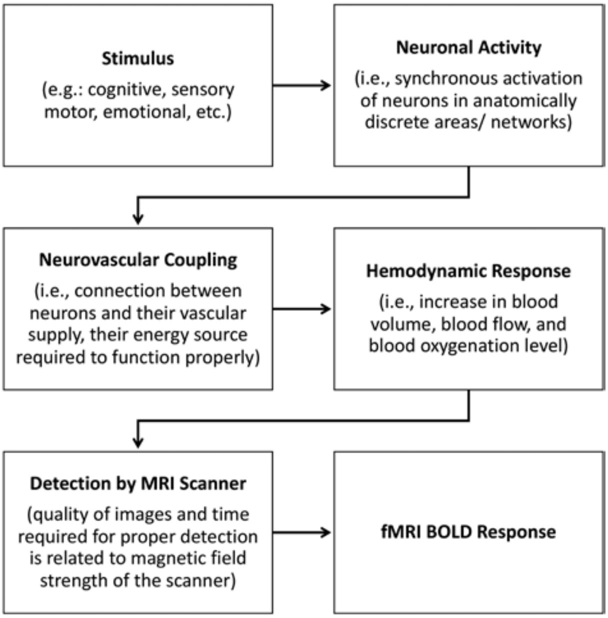

Figure 7.1 The Neural Activity Pathway. This Diagram Shows the Neural Activity Pathway, Starting from the Stimulus or Modulation of Background Activity, All the Way to the fMRI BOLD Response. *Source*: Diagram created by author.

paramagnetic when deoxygenated. This difference in magnetic properties leads to small differences in the MR signal of blood depending on the degree of oxygenation. Since blood oxygenation varies according to the levels of neural activity these differences can be used to detect brain activity. This form of MRI is known as BOLD imaging.

One point to note is the direction of oxygenation change with increased activity. You might expect blood oxygenation to decrease with activation, but the reality is a little more complex. There is a momentary decrease in blood oxygenation immediately after neural activity increases, known as the "initial dip" in the hemodynamic response. This is followed by a period where the blood flow increases, not just to a level where oxygen demand is met, but overcompensating for the increased demand. This means the blood oxygenation actually increases following neural activation. The blood flow peaks after around 4–6 seconds and then falls back to baseline, often accompanied by a poststimulus undershoot.

Just like a digital camera produces pictures with a set number of pixels, a brain scan produces 3D images that contain volumetric pixels, or *voxels* for short. In a typical scan, each voxel might cover $3mm^3$ of tissue, a volume that would encompass approximately 630,000 neurons. However, the exact size of the voxel only defines the theoretically maximal resolution. In practice, the effective resolution in fMRI images also depends on the spatial specificity of the hemodynamic response, as well as the degree of head movement during scanning. These additional factors can add substantial spatial distortion or blurring. Nevertheless, fMRI still offers a good compromise between precision and coverage, allowing the study of larger-scale network dynamics.

Although fMRI can offer reasonably good spatial resolution, it has poor temporal resolution. This is because the hemodynamic response imposes a fundamental limit on the timing of the measurement. The target peak response is typically delayed by approximately 4–6 seconds. It is possible to correct for this lag in offline post-processing analysis, but it makes it difficult to pinpoint the precise moment of a target activity. Therefore, an fMRI image can only be interpreted as an average response over many seconds (Sejnowski, Churchland, & Movshon, 2014).

FUNCTIONAL MAGNETIC RESONANCE IMAGING AND LANGUAGE RESEARCH

From Franz Josef Gall and Paul Broca, to Noam Chomsky and Steven Pinker, functional specificity, or localization of mental functions, in the human brain has been extensively debated and investigated. At the epicenter of these discussions lies the neural basis of language processing. The deconstruction of linguistic abilities and their mapping onto the brain has fueled a 200-year-old debate, one that tries to prove—or disprove—that the human brain contain "modules" that are specialized for particular linguistic operations. However, the apparent earlier evidence from brain-damaged patients for brain specializations for language has become somewhat clouded over the last ten years by a lack of parallel evidence from brain imaging. In a recent review of the brain basis of language, Blumstein (2010) argued that certain areas of the brain that have been associated with language processing appear to be recruited across cognitive domains, suggesting that while language may be functionally special, it draws on at least some neural mechanisms and computational properties shared across other cognitive domains. Fedorenko et al. (2010) argued that this apparent lack of specificity in the brain imaging literature on language processing may arise in part from the nearly exclusive use of data analysis methods that are known to underestimate functional specificity, and they argued that one possible reason why neuroimaging studies have found little consistent evidence for functional specificity of language-sensitive brain regions is that virtually all prior studies have relied on traditional group analyses, instead of studying participants' language-sensitive regions identified functionally within each subject individually. They argue that functional regions of interest (fROIs) defined within individual subjects can reveal greater functional specificity by enabling us to pool data from corresponding functional regions across subjects rather than from corresponding locations in stereotaxic space that may differ functionally because of intersubject anatomical variability.

Besides the need to account for participants' individual anatomical variability in brain imaging studies, the neural basis of language should be considered from a *neural multifunctional approach.* According to Cahana-Amitay and Albert (2014), there has been converging evidence from studies of brain damage and longitudinal studies of language in aging which supports that the neural basis of language can best be understood by the concept of *neural multifunctionality*, or the incorporation of nonlinguistic functions into language models of the intact brain, reflecting a multifunctional perspective whereby a constant and dynamic interaction exists among neural networks subserving cognitive, affective, and praxic functions with neural networks specialized for lexical retrieval, sentence comprehension, and discourse processing, giving rise to language as we know it. Evidence shows that there is a highly interactive relationship between linguistic functions and other cognitive functions.

Most research using fMRI has been dissecting the neural basis of natural language syntax and semantics by analyzing the basics of meaning composition, such as processing two-word-level to sentence-level, and even narratives. For example, Pylkkänen (2019) detected a system of composition that involves rapidly peaking activity in the left anterior temporal lobe and later engagement of the medial prefrontal cortex. Both brain regions show evidence of shared processing between comprehension and production, as well as between spoken and signed language. Both appear to compute meaning, but not syntactic structure. Previous neuroimaging research has identified a number of brain regions sensitive to different aspects of linguistic processing, but precise functional characterization of these regions has proven challenging. In a constant pursuit of the neural basis of language, three major questions drive brain imaging studies: (1) what are the brain regions involved; (2) whether those areas are in particular aspects of linguistic processing (e.g., phonological, lexico-semantic, or structural processing); and (3) whether those areas also subserve other functions.

The presence of intersubject anatomical variability along with the fact that neural networks have been shown to overlap have led to seemingly conflicting findings in fMRI studies. Whereas previous neuroimaging research has identified a large number of brain regions sensitive to different aspects of language, precise functional characterization of these regions has proven to be a seemingly incomplete approach. Prior neuroimaging results do not consistently support functional specificity of brain regions implicated in language. For example, the triangular/opercular parts of the left inferior frontal gyrus have been implicated in syntactic processing (Dapretto & Bookheimer, 1999; Santi & Grodzinsky, 2007), but other studies have implicated these regions in lexico-semantic processing (Hagoort, 2009) and phonological processing (Myers et al., 2009). Similarly, anterior temporal regions have been implicated in storing amodal semantic representations (Patterson et al., 2007), but other studies have implicated these regions in structural processing (Noppeney & Price, 2004) or in constructing sentential meanings (Vandenberghe et al., 2002).

Making use of fMRI technology, Wilson, Molnar-Szakacs, and Iacoboni (2008) conducted a study in which they presented twenty-four participants with auditory or audiovisual narratives, and used model-free intersubject correlational analyses to reveal brain areas that were modulated in a consistent way across subjects during the narratives. Conventional comparisons to a resting state were also performed. Their analyses showed the expected recruitment of superior temporal areas, but the intersubject correlational analyses also revealed an extended network of areas involved in narrative speech comprehension. These authors found that many areas in the "default mode" network (typically deactivated relative to rest) were systematically modulated by the time-varying properties of the auditory or audiovisual input, including the anterior cingulate and adjacent medial frontal cortex, and the posterior cingulate and adjacent precuneus. They also found that extensive bilateral inferior frontal and premotor regions were implicated in auditory as well as audiovisual language comprehension. The authors suggested that this extended network of regions may be important for higher-level linguistic processes, and interfaces with extralinguistic cognitive, affective, and interpersonal systems.

In the most recent models of the functional neuroanatomy of language, efforts to identify several neural interfaces among language, cognitive, motor, and sensory processes have been made. Friederici and Gierhan (2013), for example, have proposed a model comprising at least two dorsal and ventral streams, which support the processing of spoken language, from auditory perception to sentence comprehension and interact at certain points with working memory in the process. Their arguments are largely based on neuroimaging and electrophysiological studies, where carefully designed language tasks with specific contrasting features (e.g., comparison of words and pseudowords, or semantically plausible sentences to implausible ones) have been used to create highly specified brain maps for phonological, semantic, and sentential processes.

IMPORTANT CONSIDERATIONS ABOUT METHODOLOGICAL PROCEDURES

Standard Recording Devices

First, it is necessary to distinguish MRI scans from fMRI scans. MRI scans provide images of anatomical structures, like organs in the body. Unlike other types of imaging such as CT scans or PET scans, an MRI does not use X-rays. On the other hand, fMRI scans provide images of metabolic function within these anatomic structures. Therefore, fMRI is a specialized form of MRI that is used to examine the brain's functional anatomy, meaning which part of the brain is handling critical functions, by measuring small changes in blood flow that occur over time with brain activity.

Currently available MRI scanners vary in terms of magnetic field strength measured in Tesla (T), which can range from 0.35 to 10.5T. The increase of the magnetic field strength goes hand in hand with changes in physical features such as signal-to-noise-ratio, tissue susceptibility, chemical shift, or radiofrequency effects, yielding potentially beneficial as well as disadvantageous effects (Budinger et al., 2016; Ertuk et al., 2017; Laader, 2017; Kuhl et al., 2008). Furthermore, an MRI machine can be used for both MRI and fMRI scans. MRI scanners can be closed, open, wide bore, extremity, and open upright.

Closed MRI Scanners

A closed MRI is a machine that takes detailed images of a person's anatomy in a narrow cylindrical container normally spanning a bore diameter of approximately 50–60 centimeters (see figure 8.2). A closed MRI can be a lot more powerful than open MRIs, currently going all the way up to 10.5T, making the closed MRI scanner the most accurate alternative available. In closed MRI scanners, the patient lies in a very narrow space in a "tube-like" structure for the test. However, many patients have reported feeling claustrophobia during the exam or experiment.

Open MRI Scanners

An open MRI scanner was created to offer an alternative to patients who either have symptoms of anxiety or suffer from claustrophobia or obesity due to the enclosed nature and duration of study normally attributed to closed MRIs. While the open MRI excels at providing comfort, it does not provide the same level of detail as a closed MRI at this time. See an example of a closed MRI on the left and an open MRI on the right. An open bore MRI (magnetic resonance imaging) system differs from a traditional MRI by the size of the opening, or bore, in which the patient lies within a large cylindrical magnet. Allowing for more space in the Open MRI scanner does have its own drawbacks. The magnet size in Open MRI scanners starts at 0.35T to 0.7T and currently tops out around 1.2T. The result is reduced image quality when compared to Closed Bore MRI. Although an open MRI offers increased comfortability for patients suffering from anxiety or claustrophobia, it comes at the cost of producing less detailed images than its closed MRI counterparts because the open nature of the machine does not provide as strong of a magnetic field. Open bore MRIs canner can range from 0.2T to 1.2T. Depending on the magnetic field strength, session can range from 45 minutes to 1 hour.

Wide Bore MRI Scanners

Wide bore MRI is also referred to as open bore. It combines the benefits of closed bore MRI with more space inside the bore area of the machine. The wide bore MRI system delivers both high magnet strength and high-quality imaging, and the procedure is shorter in duration than an open MRI. It is ideal for larger patients and patients that would otherwise get claustrophobic because it has a 70-centimeter opening. Wide bore MRI scanners can go up to 1.5T, so sessions are shorter than those using an open bore scanner, and take around 15–20 minutes.

Extremity MRI Scanners

An extremity MRI scanner is a diagnostic imaging procedure that uses a closed MRI machine to look at the tissues in the arms and legs. Unlike a traditional MRI procedure that uses a large tube-shaped device, an extremity MRI uses a smaller scanner designed specifically for the body's extremities. This eliminates the potential for claustrophobia, which some patients experience when enclosed in a full-body MRI machine. A traditional MRI requires you to lie completely still, but an extremity MRI won't limit your body movements quite as much. One may undergo an extremity MRI to diagnose any of the following conditions in the arms, legs, hands, and feet, like arthritis, fractures, bone infections, tumors of the bone or soft tissue, nerve-related issues, stress injuries or injuries related to torsion or heavy impact, and so on.

Open Upright MRI Scanners

Open upright MRI scanners (also called "multiposition" or "vertical open" MRI scanners) offer the ability to capture images of a person's body in various positions such as sitting, standing, bending, leaning, or twisting. All other MRIs can only scan patients lying down. Open upright MRI scanners' magnetic field strength typically range from 0.5T to 0.6T.

Why Use fMRI Scanners in Conjunction with EEG?

An fMRI scanner can be used to generate structural scans of high *spatial* precision, representing an accurate and highly precise 3D rendering of the participant's brain, but as explained before, it has low temporal resolution. Structural scans obtained with fMRI are particularly useful when combining them with surface EEG recordings. In this case, the spatial precision of the fMRI meets the temporal resolution of the EEG, so combining both allows for sub-second reconstructions of generator sources of brain activity associated with cognitive or behavioral processing, which is not possible using each method on its own.

Recommendations for Data Collection

The development of MRI techniques has defined modern neuroimaging. Since its inception, tens of thousands of studies using techniques such as functional MRI and diffusion weighted imaging have allowed for the non-invasive study of the brain. Despite the fact that MRI is routinely used to obtain data for neuroscience research, there has been no widely adopted standard for organizing and describing the data collected in an imaging experiment. This renders sharing and reusing data (within or between labs) difficult if not impossible and unnecessarily complicates the application of automatic pipelines and quality assurance protocols. To solve this problem, we have developed the Brain Imaging Data Structure (BIDS), a standard for organizing and describing MRI datasets. The BIDS standard uses file formats compatible with existing software, unifies the majority of practices already common in the field, and captures the metadata necessary for most common data processing operations. For a detailed overview of procedures for describing outputs of neuroimaging experiments, see Krysztoff et al. (2016). For examples of studies that list detailed protocols that might be useful for other studies, see Dewey et al. (2018) and Panta et al. (2016).

Recommendations for Data Processing

There are many ways to analyze an fMRI dataset, especially when many of the available analysis approaches make sense and can be easily justified. However, different choices generate slightly different results. Although this flexibility is not strictly a limitation in fMRI analysis (and certainly not unique to fMRI), it is definitely something to keep in mind when interpreting the data in the fMRI literature. It is important to define the analysis pipeline independently of the research question, rather than trying different ones and selecting the one that gives the "best" results. This could potentially bias the analysis and misguide the results.

Neuroimaging is a broad field, encompassing a range of approaches across a growing number of modalities. fMRI studies are expensive and are often single studies or have a small pool of participants. In addition, the rigor and reproducibility of neuroimaging research has been questioned due to a number of interrelated issues including reporting and publication biases in the scholarly literature, low levels of statistical power, the use of suboptimal design and analytical methods, and the recent discovery of errors in widely used software tools. Open data sharing has long been proposed as a way to address such issues, but sharing neuroimaging data does not directly address shortcomings in research design or analytical methodology within single studies. For data to be effectively shared, evaluated, and reused, it must first be effectively documented, organized, saved, and prepared. Such activities are encapsulated in the findable, accessible, interoperable, and re-usable (FAIR) framework (Borghi & Van Gulick, 2018).

Another important consideration to keep in mind when analyzing fMRI data is the problem of reverse inferences. An examination of the discussion sections of a few fMRI articles will quickly reveal an trend of reasoning taking the following form: (a) in the present study, when task A was presented, brain area Y was active; (b) in other studies, when cognitive process X was putatively engaged, brain area Y was active; (c) therefore, the activity of area Y in the present study demonstrates engagement of cognitive process X by means of task A. This is called a “reverse inference,” in that it reasons backwards from the presence of brain activation to the engagement of a particular cognitive function. However, reverse inferences are not a valid form of deductive reasoning in fMRI data because there might be other cognitive functions that activate the same brain area. Nevertheless, the general form of reasoning can provide useful information, especially when the function of the particular brain area is relatively specific and particularly well-understood. Using accumulated knowledge to interpret new findings is necessary for theory building. However, in the absence of a strict one-to-one mapping between structure and function, reverse inference is best approached from a Bayesian perspective from which the probability of a finding is interpreted as a reasonable expectation representing a state of knowledge in the field.

Next, it is required to point out here that fMRI can only provide correlational evidence. The same can be said for any other physiological measurement technique. When a certain brain area lights up with a specific mental function, it does not necessarily mean that the observed activity actually caused the mental event. Only an interference approach can provide such causal evidence. For example, if we “knock-out” a specific area (as in the event of brain damage) and observe a specific impairment in behavior, then it is possible to infer that the targeted area normally plays a causal role in that behavior. Although this is strictly correct, this does not necessarily imply the causal methods are better. Neural recordings can provide enormously rich insights, albeit correlational, into how brain activity unfolds during normal behavior. By contrast, causal methods allow you to test how the system behaves without a specific area. But because there is likely to be redundancy in the brain (multiple brain areas capable of performing the same function), interference approaches are susceptible to missing important information. Moreover, perturbing the neural system is likely to have repercussions that are difficult to control for, thereby complicating the analysis of the results.

Last but not least, despite the wealth of tools available for neuroimaging processing and analysis, there is still a need to increase reproducibility. Aside from the importance of carefully reporting the study design, methods, and results mentioned above, archiving of statistical results, software engineering for reproducibility, and optimizing projects for generalizability should be prioritized. Computational reproducibility relies on familiarity with modern software engineering practice. Whether the analysis uses a small set of scripts or a comprehensive end-to-end pipeline, neuroimaging data analysis depends on coding. Modern software engineering includes practices like version control and unit testing. Version control ensures that revisions of the code are identifiable and archived, and ideally it is based on an open platform that allows wide inspection and input; unit tests verify the correctness of individual facets of the code and can be set to automatically run each time the code is updated. This is not to say that every group should hire a programmer but rather that every researcher writing scripts or code should obtain proficiency with basic software engineering skills and practices (Nichols et al., 2017).

Chapter 8

Eye Movement and Eye Tracking

A BRIEF OVERVIEW OF EYE MOVEMENT AND EYE TRACKING

Eye tracking refers to the measurement of eye movement activity. This technique describes the recording of eye position and movement in an environment based on the optical tracking of corneal reflections to assess point of gaze and visual attention. In other words, eye tracking is a technique in which an individual's eye movements are measured so that the researcher knows where that individual is looking at, how long the gaze stayed at each particular focus point, and the sequence in which that person's eyes shifted from one location to another.

Throughout the history of eye-tracking research, several key variables have emerged as significant indicators of ocular behaviors, including fixations, pupil dilation, and scan paths (Rayner, 1998). *Eye fixations* are defined as a spatially stable gaze lasting for approximately 200–300 milliseconds, during which visual attention is directed to a specific area of the visual display. If a series of gaze points is very close in time and in space, this gaze cluster constitutes a *fixation*, denoting a period where the eyes are locked toward an object. *Pupil dilation* is typically used as a measure to gauge an individual's interest or arousal in the content they are viewing. The eye movements between fixations are generally referred to as *saccades*. *Scanpaths* are the pattern of eye movements that occur when a person processes a stimulus (Rayner, 1998). For example, when we read, our eyes do not travel smoothly. We lock our eyes toward every third or fourth word, going through groups of words that typically constitute a word cluster. The term *visual span* refers to how many words we can read before and after the currently fixated word (trained readers have a higher visual span, allowing them to cover more text with fewer fixations). Another term widely used in eye movement research is *heatmap*. Heatmaps are visualizations that show the general distribution of fixations and gaze points. They are therefore indicators of the participant's attention, with red areas suggesting a high number of gaze points (increased level of attention), followed by yellow and green. Heatmaps can be generated for single respondents as well as for a full study of several participants. In this case, eye-tracking heatmaps are an excellent method to visualize which elements attract more attention than others (figure 8.1).

In addition, there are four basic types of eye movements: saccades, smooth pursuit movements, vergence movements, and vestibulo-ocular movements. The functions of each type of eye movement are introduced below:

Saccades

Saccades are rapid, ballistic movements of the eye that abruptly change the point of fixation by repositioning the fovea (see figure 8.2) to a new location in the visual environment (Duchowski, 2017). The fovea is a small, central protuberance in the eye that is located in the center of the macula lutea of the retina and is composed of closely aligned cones. The fovea is responsible for sharp central vision, which is required for activities where visual detail is of primary importance, such as when reading, inspecting small components

Figure 8.1 iMotions Software that Calculates and Displays Heat Maps. *Source*: Image courtesy of iMotions, Inc.

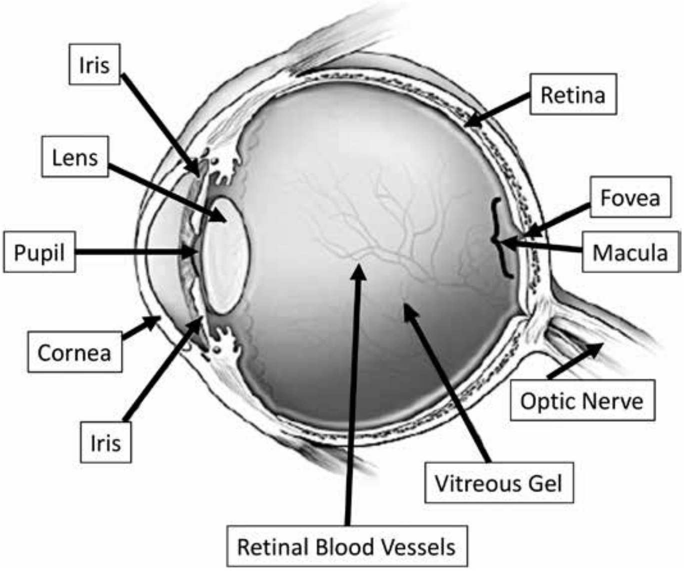

Figure 8.2 The Eye Anatomy. Diagram Showing the Location of the Fovea and Other Regions of the Eye Anatomy. *Source*: Diagram created by author.

of electronics, or driving. They range in amplitude from the small movements made while reading, for example, to the much larger movements made while gazing around a room. Saccades can be elicited voluntarily, but occur reflexively whenever the eyes are open, even when fixated on a target. The rapid eye movements that occur during an important phase of sleep are also saccades.

Smooth Pursuit Movements

Smooth pursuit movements are involved when visually tracking a moving target. Depending on the range of target motion, the eyes are capable of matching the velocity of the moving target (Duchowski, 2017). Smooth pursuit movements are much slower tracking movements of the eyes designed to keep a moving stimulus on the fovea. Such movements are under voluntary control in the sense that the observer can choose whether or not to track a moving stimulus.

Vergence Movements

Vergence movements align the fovea of each eye with targets located at different distances from the observer. Unlike other types of eye movements in which the two eyes move in the same direction (i.e., conjugate eye movements), vergence movements are disconjugate (i.e., disjunctive) and they involve either a convergence or a divergence of the lines of sight of each eye to see an object that is nearer or farther away.

Vestibulo-ocular Movements

Vestibulo-ocular movements stabilize the eyes relative to the surrounding environment, compensating for head movements. These reflex responses ensure that visual images stay on the surface of the retina as head position varies. One can appreciate the action of vestibulo-ocular movements by fixating on an object and moving the head from side to side; the eyes automatically compensate for the head movement by moving the same distance but in the opposite direction, thus keeping the image of the object at more or less the same place on the retina.

Eye Muscles

There are six muscles responsible for movement of the eyeball: the *medial* and *lateral recti* (for sideways movements), the *superior* and *inferior recti* (for up/down movements), and the *superior* and *inferior oblique*. The neural system involved in generating eye movements is known as the oculomotor plant (Robinson, 1968). Eye movement control signals emanate from several functionally distinct regions. Some of these regions are located in the occipital cortex, which are thought to be responsible for high-level visual functions such as recognition. The superior colliculus bears afferents emanating directly from the retina, particularly from peripheral regions conveyed through the magnocellular pathway (magnocellular neurons are located within the magnocellular layer of the lateral geniculate nucleus of the thalamus, and are part of the visual system). The semicircular canals react to head movements in three-dimensional space. These three areas (i.e., the occipital cortex, the superior colliculus, and the semicircular canals) convey efferents to the eye muscles through the *mesencephalic* and *pontine* reticular formations. Classification of observed eye movement signals relies in part on the known functional characteristics of these cortical regions (Duchowski, 2017).

Areas of Interest

An area of interest, also referred to as AOI, is a tool to select subregions of the displayed stimuli and to extract metrics specifically for these regions. For example, if the experimenter shows participants pictures of a person, it is possible to draw separate AOIs around the body and the face of the stimulus. Then the experimenter would be able to display metrics for each region separately, as in how much time from stimulus onset has elapsed until participants looked into the region (time to first fixation, TTFF), how much time participants spent in the region, how many fixations were counted, and how many people looked away and back (how many revisits there were).

Time to the First Fixation

The *time to the first fixation* reports the amount of time that it takes a participant to look at a specific AOI from the stimulus onset. TTFF can also indicate both bottom-up stimulus-driven searches and top-down attention-driven searches.

Time Spent

Time spent quantifies the amount of time that participants have spent on an AOI. Time spent often indexes motivation and top-down attention since participants have to blend out other stimuli in the visual periphery that could be equally interesting. Long periods at a certain region clearly indicates a high level of interest, while shorter periods indicate that other areas on screen or in the environment might be more interesting.

Ratio

The *ratio* allows extracting information about how many of your participants actually guided their gaze toward a specific AOI. A higher ratio might indicate that fixations and gaze points are driven rather by external aspects in the stimulus material (bottom-up), or that the target group is very consistent in looking toward a specific AOI while ignoring others.

Fixation Sequences

Based on fixation position and timing information, the experimenter can generate a *fixation sequence*. As the participant's eyes screen an environment, they wander, and so does their attention. Depending on where participants look and how much time they prevail, the experimenter can build an order of attention to track where participants looked at first, second, third, and so on. *Order of attention* is a commonly used marker in eye-tracking research, and it reflects the participant's interest as well as "salient" elements in the stimulus.

EYE MOVEMENT AND EYE TRACKING AND LANGUAGE RESEARCH

Eye tracking in human behavior research unlocks several interesting measures such as attention, interest, and arousal. Research questions can range from studying what participants find interesting in videos to what elicits their attention when reading or looking at an image in a textbook or on a computer screen. In order to answer these questions, researchers can use eye trackers and software that draw heatmaps of accumulated gaze positions overlaid on the presented stimulus.

Most eye-tracking studies aim to identify and analyze patterns of visual attention of individuals as they perform specific tasks (e.g., reading, searching, scanning an image, solving a problem, etc.). In these studies, eye movements are typically analyzed in terms of fixations and saccades. The brain virtually integrates the visual images that we acquire through successive fixations into a visual scene or object. Furthermore, we can only combine features into an accurate perception when we fixate and focus our attention on them. The more complicated, confusing or interesting those features are, the longer a person takes to process them and, consequently, more time is spent fixating on them. In most cases, something can only be perceived and interpreted clearly when fixating on an object or if it is close by. This eye-mind relationship is what makes it possible to use eye movement measurements to explain this kind of behavior.

Eye Movements and Attention

Although it is often necessary to move our eyes to identify objects in our environment, it is possible to shift the focus of attention without moving our eyes, which poses a problem in eye-tracking research. It is possible to visually fixate one location while simultaneously diverting attention to another. To illustrate how this would work in real life, imagine you are surrounded by a ridge of mountains, and as you are scanning the horizon, you fixate your gaze upon the top of one particular mountain that is very far away; then you fixate your gaze upon the top of a higher mountain just behind it, whose peak is not much higher than the peak in front of it. In this situation, you shifted your focus of attention without moving your eyes. When examining a scanpath over a visual stimulus, we can often say that a certain region was looked at, perhaps even fixated (following analysis of eye movements); however, we cannot be fully confident that specific region was fully perceived. There is no simple way of telling what the brain is doing during a particular visual scan of the scene without also recording one's brain activity (Duchowski, 2002, p. 456). In such cases, research experiments often look for brain activity in the prefrontal cortex, which is an area that is largely thought to be central to the ability to shift attention and choose actions appropriate to the sensory information at hand, taking into account to the specific sensory, motor, and cognitive demands in which the task is encountered (Asaad, Rainer, & Miller, 2000).

Eye Movements and Brain Imaging

Eye movement recording and functional brain imaging have been used to track a research participant's fixation point while simultaneously recording cortical activation during attentional tasks in order to identify functional brain structures implicated in attentional behavior. One example of such research methodology is Özyurt, DeSouza, West, Rutschmann, and Greenlee (2001) study. They compared the neural correlates of visually guided saccades in the step and gap paradigms while recording saccadic eye movements during task performance. The results from Özyurt et al.'s study indicated significant task-related activity in the striate and extrastriate cortex, the frontal eye fields, the supplementary motor area, the parietal cortex and angular gyrus, the frontal operculum, and the right prefrontal area. This type of research helps identify functional brain structures that participate in attentional mechanisms.

Eye Movements and Reading

Perhaps the first well-known use of eye trackers in the study of human (overt) visual attention occurred during reading experiments. Rayner (1992, 1998) has provided an excellent survey of eye-tracking applications in reading and other information-processing tasks. Rayner's (1998) article for the complete review, three interesting examples of eye movement characteristics during reading will be summarized here. First, when English is read, eye fixations last about 200–250 milliseconds, and the mean saccade size is from seven to nine letter spaces. Second, eye movements are influenced by textual and typographical variables—for example, as text becomes conceptually more difficult, fixation duration increases and saccade length decreases. Factors such as the quality of print, line length, and letter spacing influence eye movements. Third, eye movements differ somewhat when one reads silently from when one reads aloud: Mean fixation durations are longer when one reads aloud or while one listens to a voice reading the same text than when one reads silently. There is of course a good deal more that has been learned (e.g., Reichle, Pollatsek, Fisher, & Rayner, 1998, summarized some basic data on reading and eye movements related to their subsequent effort to model the reading process); here, the methodology behind such discoveries is what is of primary interest.

Eye Movements and Scene Perception

Although certain reading patterns are easily recognized (e.g., left to right and top to bottom for English readers or right to left for Hebrew readers), no apparent strategies for scene viewing have been easily discerned. Contrary to reading, there appears to be no canonical scan path for particular objects (Kennedy, 1992). There may be context differences at play. Kroll (1992) stated that although there may be similarities between reading and scene-viewing tasks, the tasks are very different.

According to Henderson and Hollingworth (1998), there are at least three important reasons to understand eye movements in scene viewing. First, eye movements are critical for the efficient and timely acquisition of visual information during complex visual-cognitive tasks, and the manner in which eye movements are controlled to service information acquisition is a critical question. Second, how we acquire, represent, and store information about the visual environment is a critical question in the study of perception and cognition. The study of eye movement patterns during scene viewing contributes to an understanding of how information in the visual environment is dynamically acquired and represented. Third, eye movement data provide an unobtrusive, online measure of visual and cognitive information processing.

Joint Attention (JA) and Brain Imaging

JA, which is characterized as the shared attentional focus of at least two people on a third significant object, is one of the earliest steps in social development and an essential aspect of reciprocal interaction. However, the neural basis of JA in the course of development is not well known. A study conducted by Oberwelland et al. (2016) investigated the behavioral and neural correlates of JA when self- and other-initiated, as well as the role of familiarity of the interaction partner. They made use of an interactive eye-tracking and fMRI study design in order to examine the developmental trajectories of JA and the influence of a familiar interaction partner during the experiment. Their results showed that, compared to adults, children and adolescents' JA elicits a similar network of *social brain* areas (including the key nodes VS, TPJ, pSTS, amygdala), attention, and motor control areas (e.g., precentral gyrus, MFG, inferior parietal gyrus). While other-initiated JA particularly recruited visual, attention, and social processing areas, self-initiated JA specifically activated areas related to social cognition, decision-making, emotions, and motivational/reward processes, which suggests a rewarding component of self-initiated JA. The importance of the results obtained by Oberwelland et al. is that they help us better understand the development of social interaction and communication as well as overall social cognition during development.

IMPORTANT CONSIDERATIONS ABOUT METHODOLOGICAL PROCEDURES

Eye-tracking analysis is based on the premise that there is a correlation between fixations, gaze, and underlying cognitive processes. However, there are a few factors that need to be considered before inferring these correlations or making other assumptions about the data.

First, fixations do not necessarily translate into a single kind of cognitive process. For example, during a search task, one might fixate briefly on the search object and miss its presence, especially if the object has an unexpected shape or size (*change blindness*). This happens because our expectation of what the object should look like modulates our visual attention and interferes with the object detection. This effect can be eliminated from an experiment if you give clear instructions to the participant, or follow up with an exit interview to assess what the participant's motivations or expectations were.

Second, fixations can be interpreted in different ways depending on the context and objective of the study. For example, if the experimenter instructs a participant to freely browse a newspaper and they observe a higher number of fixations on one particular area of the page, it can indicate that either the participant has found an object of particular interest in that area (e.g., a photograph or a caption) or that particular area has a very complex and hard to encode object. However, if the experimenter gives the participant a specific search task, a higher number of fixations are often indicative of confusion and uncertainty in recognizing the elements necessary to complete the task. Again, a clear understanding of the objective of the study and careful planning of the tests is important for the interpretation of the eye-tracking results.

Third, during the processing of an image, individuals will move their eyes around, in the process of locating various relevant features. Some of these features may be primarily detected in the peripheral field of vision. Due to its low acuity, a feature located in this area will lack shape or color detail, but the study participant is still able to use it to recognize well-known structures and forms as well as make quick, general shape comparisons between scenes. This implies that participants would also use their peripheral vision to filter features according to their relevance. For example, when browsing a website, most people avoid looking at advertisement banners, so they might also avoid moving their eyes to other sections of the webpage that have a similar shape because their peripheral vision has tagged them as potential banners. An eye tracker may show the areas on the visual scene that a study participant has fixated on, or areas that were jumped, but not what was "seen" in the peripheral field of vision. Thus, to fully understand why a test participant has been ignoring an area of the visual stimulus, it is important that the tests be accompanied by an exit interview or think-aloud protocols.

Standard Recording Devices

The measurement device most often used for measuring eye movements is commonly known as an eye tracker. In general, there are two types of eye movement monitoring techniques: those that measure the position of the eye relative to the head and those that measure the orientation of the eye in space, or the point of regard.

Measurement precision certainly is crucial in eye movement research. The quality of the collected data depends primarily on the tracking accuracy of the device you use. Going for a low-quality system will prevent you from being able to extract high-precision data. A common misconception is that researchers face an inevitable tradeoff between measurement accuracy and the amount of movement the respondent can make with their head. The truth is a bit more complex than that. First of all, there are two kinds of trackers: the screen-based eye trackers and the eye-tracking glasses. The screen-based eye trackers require respondents to sit in front of a screen or close to the stimulus being used in the experiment. Although screen-based systems track the eyes only within certain limits, they are able to move a limited amount, as long as it is within the limits of the eye tracker's range. This range is called the headbox. The freedom of movement is still sufficiently large for respondents to feel unrestricted. The eye-tracking glasses, on the other hand, are fitted near the eyes and therefore allow respondents to move around as freely as they would like—certainly a plus if your study design requires respondents to be present in various areas (e.g., a large lab setting, or a supermarket). As long as the device is calibrated properly, head-mounted eye trackers are unaffected by head movements and deliver high-precision gaze data just like screen-based devices. Also, as the eye-tracking camera is locked to the head's coordinate system, the overlaying of eye movements onto the scene camera does not suffer from inaccuracies due to head movement. Below are some of the eye trackers commonly used in published scientific articles.

EyeLink 100 Plus, EyeLink Duo, Eye Link II Eye Trackers

One example of a company that specializes in eye trackers is SR Research. They manufacture the EyeLink line of eye trackers. Their eye trackers are renowned for their exceptional levels of accuracy and precision, combined with high sampling speeds. EyeLink eye trackers can be integrated with a wide range of other devices, allowing recordings to be precisely synchronized.

Tobii

Another company that has a good reputation in the manufacturing of eye trackers is the Tobii Group. The Tobii Group created an eye tracker that comes with custom-designed sensors. Their hardware is designed to be a high-performance sensor, and it consists of custom-designed projectors, customized image sensors and optics as well as custom processing with embedded algorithms. Tobii eye trackers are marketed to be used for human behavior research as well as assistive technology, consumer insight research, virtual reality, targeting the gaming industry. The Tobii Dynavox specializes in assistive technology for communication, Tobii Pro supplies eye-tracking solutions for human behavior research, and Tobii Tech integrates with consumer electronics such as gaming devices.

Video-Based Combined Pupil and Corneal Reflection

This method is relatively inexpensive, and it utilizes cameras and image processing hardware to compute the point of regard in real-time. This kind of apparatus may be table-mounted or head-mounted (wearable). Except for size, the optics of either system are virtually identical.

Two points of reference on the eye are needed to separate eye movements from head movements. Due to the construction of the eye, four corneal reflections are formed. One corneal reflection of the light source (which is typically infrared) is measured relative to the location of the pupil center. Video-based eye trackers typically locate the first corneal image, and with appropriate calibration procedures, these eye trackers are capable of measuring a viewer's point of regard on a perpendicularly positioned surface on which calibration points are displayed.

These devices are becoming increasingly accessible as there is a growing number of manufacturers producing them. Eye tracking as a research tool is more accessible than ever, and is growing in popularity among researchers from a whole host of different disciplines. Usability analysts, sport scientists, cognitive psychologists, reading researchers, psycholinguistic, neurophysiologists, electrical engineers, and others all have a vested interest in eye tracking for different reasons. There is no doubt that it is useful to record eye movements; it advances science and leads to technological innovations.

Virtual Reality (VR) and Eye Tracking

A very promising emerging trend in behavioral neuroscience is the use of VR technology to conduct experiments in order to elicit more realistic participation and results. The types of thought processes and emotions that would be evoked in real life are more likely to be generated during a VR experiment. Several studies have shown that participants' subjective, behavioral, and physiological responses in VR environments map their behavior and experience in real-world settings (Bunge & Skulmowski, 2014; Carassa et al., 2005; Skulmowski et al., 2014; Rovira, 2009; Slater et al., 2006). Most importantly, it is possible to link additional physiological measurement equipment to a VR device in order to monitor and record online physiological measures of emotional arousal during experiments.

Recommendations for Data Collection

Performance measurement in experiments that use eye-tracking devices should incorporate ethnographic information, co-discovery, or think-aloud protocols whenever possible. Think-aloud is certainly a valuable feedback technique, but it must be used wisely. This is due to the fact that it may change how a participant performs during a task since it may potentially alter their gaze patterns (Bojko, 2005) as well as timing because they would need to talk while performing the task. A more productive manner of using think-aloud protocols was proposed by Guan et al. (2006); they suggest that the participant could verbalize actions during a *retrospective* think-aloud session. In this way, because the task would have already been completed, performance metrics would remain reliable. More importantly, however, retrospective examination of one's scanpath could trigger recollection of some difficulty the participant may have experienced during the session, and replay of their eye movements may result in richer data understanding.

During data collection, the researcher must take into account the difference between *subjective* metrics and *objective* metrics. *Subjective* metrics are related to eliciting information about participants' satisfaction, learnability, helpfulness, control, efficiency, and affect. These questions should provide a limited range of responses in a quantifiable form, such as a Likert scale. On the other hand, *objective* measures can be divided into performance measures and process measures. The performance measures relate to efficiency (as in time to complete task) and effectiveness (e.g., number of errors committed). Process measures relate to the number of fixations found in the study, fixation durations, attentional switching, and scanpath similarity, which is a potential indicator of position and sequence similarity among different viewers (Duchowski, 2017). In addition, the following information must be taken into account and reported in eye-tracking studies:

System Identification

The system to be used for eye movement capture needs to be identified and reported. This is usually listed in the "apparatus" section of a study report and should include the operating characteristics of the eye tracker.

Constraints

There are (at least) three operational constraints associated with system evaluation: time, personnel, and money.

Selection of Participant

Clearly planning for a large number of participants will increase the expected duration of the study. User selection therefore is related to study duration, which is one of the three important operational constraints.

Evaluation Location

The evaluation location must be decided prior to conducting the study. If a setup lab is not available, it is possible to either use a head-mounted eye tracker or a table-mounted eye tracker to conduct an in-field eye-tracking study, as long as it is kept somewhat consistent across the entire experiment.

Task Selection

Task selection may be the most critical consideration of all, particularly for eye-tracking studies. Because eye movements (and attention) are deployed as a combination of bottom-up (stimulus-driven) and top-down (goal-driven) cognitive processes, the nature of the task will influence eye-tracking outcomes (the scanpaths). Eye movements are task-dependent and therefore the tasks must be chosen with care. For example, Dix et al. (2004) provide the following succinct list of task analysis techniques and sources of information: (1) task analysis techniques should include decomposition of tasks into subtasks; taxonomic classification of task knowledge; listing actions performed and tools used; (2) sources of information should include all existing documentation, observation, and interviews.

Environment and Lighting Conditions

The researcher should find a dedicated space for running the study, like an isolated room that is not used by others so that they can keep their experimental setup as consistent for each participant as possible. They should also make sure to place all system components on a table that does not wobble or shift. For eye tracking, lighting conditions are essential. It is highly desirable to avoid direct sunlight coming through windows (e.g., the researcher could close the blinds) as sunlight contains infrared light that can affect the quality of the eye-tracking measurements. Avoid brightly lit rooms or overhead light. Ambient light is preferable. It is particularly important to keep the lighting levels consistent when measuring levels of pupil dilation (pupillometry). This also applies to the luminance of the stimulus. The researcher should avoid designing long experiments as they might cause dry eyes, resulting in eye drift. Finally, the researcher should try to keep noise from the surrounding environment (e.g., rooms, corridors, streets) at a minimum, as it could distract the respondent, resulting in drift, and affect measurement validity.

Recommendations for Data Processing

The software that accompanies the eye tracker typically provides the following information that is required for analysis: pupil size and dilation, distance to the screen, ocular vergence, and number of blinks and blinking patterns. An increase in pupil size is referred to as pupil dilation, and a decrease in size is called pupil constriction. Pupil size primarily responds to changes in light (ambient light) or stimulus material (e.g., video stimulus). However, if the experiment can account for light, other attributes can be derived from changes in pupil size. Two common properties are emotional arousal (referring to the amount of emotional engagement) and cognitive workload (which refers to how mentally taxing a stimulus is). Along with pupil size, eye trackers also measure the distance to the screen and the relative position of the respondent. Leaning forward or backward in front of a remote device is tracked directly and can reflect approach-avoidance behavior. However, keep in mind that interpreting the data is always very specific to the application. Most eye trackers measure the positions of the left and right eyes independently. This allows the extraction of vergence, that is, whether left and right eyes move together or apart from each other. This phenomenon is just a natural consequence of focusing near and far. Divergence often happens when our mind drifts away, when losing focus or concentration. It can be picked up instantly by measuring interpupil distance. Eye tracking can also provide essential information on cognitive workload by monitoring blinks. Cognitively demanding tasks can be associated with delays in blinks, the so-called attentional blink. However, many other insights can be derived from blinks. A very low frequency of blinks, for example, is usually associated with higher levels of concentration. A rather high frequency is indicative of drowsiness and lower levels of focus and concentration.

Chapter 9

Respiration

A BRIEF OVERVIEW OF RESPIRATION

The Respiratory System

Most of the respiratory system is contained within the thorax, apart from the upper airways in the subglottal vocal tract. The thoracic cage is made up of twelve ribs to which muscle and connective tissue attach posteriorly to the vertebral columns and anteriorly to the breast bone (sternum). On the vertical axis, the thoracic cage is limited by the shoulder blades (scapulae) on the posterior side and the collar bones (clavicles) on the anterior side, and by the diaphragm as its base (Clark, Yallop, & Fletcher, 2007). Inside the thoracic cage are the lungs, which are connected to the windpipe (i.e., trachea) by two bronchial tubes. Both lungs consist of smaller tubes (bronchioles) ending with tiny air sacs (alveoli). The lungs are connected to the thoracic cage by the pleural linkage, thus forming a single mechanical unit capable of changing the air volume in lungs when the thoracic cage volumes change during the respiratory cycle. Besides performing the vital function of replenishing oxygen and removing carbon dioxide from blood, the lungs provide most of the airflow reservoir necessary for speech production.

Inhalation

During inhalation, the volume of the thoracic cavity is enlarged in two ways: (1) the rib cage is lifted upward and outward and (2) the floor of the cavity is lowered. The exact balance between the two movements depends on posture and respiratory demands. In general, the external intercostal muscles situated between the ribs are responsible for the control of the rib cage dynamics during inhalation. When they contract, the distance between each rib is shortened, raising the rib cage structure, and increasing the thoracic cavity volume. When the diaphragm contracts, it lowers the floor of the thoracic cavity. This action is responsible for inspiratory thoracic cavity changes during quiet breathing. In running speech, the diaphragm has control over increasing the volume of the thoracic cavity for inhalations. Any enlargement of the thoracic cavity results in an increase in lung volume.

Exhalation

Reducing thoracic volume, and consequently lung volume, increases the internal air pressure and results in air flowing out of the lungs in order to equalize the internal and external air pressures. The elastic recoil forces set up by the expansion and movement of muscles during inhalation are enough to achieve the necessary lung volume reduction toward relaxation pressure. Hixon (1987) proposes that these forces governing both expansion and reduction can be thought of as a spring-like force: if stretched and then released, the spring will rapidly recoil back to its original position. At lung volumes above the resting level, this relaxation is the result of a passive exhalation generated by positive (i.e., above atmospheric) pressure toward resting level. When lung volumes are below resting level, this process is reversed, as lungs inflate from residual volume to the resting expiratory level due to the increasing magnitude of subatmospheric pressure.

Lung Volumes

Volume is one of the key variables controlling respiration. The air displaced by the respiratory apparatus is called lung volume, and it corresponds to the change of volume of the thoracic cage. There are four lung volumes, each exclusive of the other, and four lung capacities which are the sum of two or more lung volumes (see next section). The tidal volume (TV) is the volume of air inhaled or exhaled during breathing, measured while resting. The resting point of the rib cage and lungs is just at the expiratory-end level of the TV and is referred to as the resting expiratory level (REL) (Cleveland, 1998). The extra volume of air that can be inspired with maximal effort after reaching the end of a normal, quiet inspiration is the inspiratory reserve volume (IRV), and the expiratory reserve volume (ERV) is the amount of extra air, above a normal breath, that can be exhaled during a forceful breath out. The average ERV volume is about 1100 mL in males and 800 mL in females (Hixon, 2006). At the end of a maximum exhalation, the volume of air left in the pulmonary apparatus is called the residual volume (RV).

Lung Capacities

Another key variable controlling respiration is lung capacity. There are four lung capacities: the vital capacity (VC), or the maximum volume of air that can be exhaled after a maximum inhalation; inspiratory capacity (IC), or the maximum volume of air inhalable from the resting level; the functional residual capacity (FRC), or the volume of air in the pulmonary apparatus at the resting tidal end-expiratory level; and total lung capacity (TLC), or the maximum amount of air in the pulmonary apparatus achievable after a maximum inhalation. Although lung capacities vary greatly depending on a person's age, gender, posture, and body type, a typical capacity for an adult male is within 5–7 liters of air. In that case, the VC ranges from 3.5 to 5 liters. During quiet breathing, the amplitude of exhalable and inhalable air is around 0.5 liters, and it normally makes up about 10%–15% of VC (Clark et al., 2007; Hixon, 2006).

In addition, a person who is born and lives at sea level will develop a slightly smaller lung capacity than a person who spends their life at a high altitude. This is because the partial pressure of oxygen is lower at higher altitude which means that oxygen diffuses into the bloodstream less readily. In response to higher altitude, the body's diffusing capacity increases in order to process more air. Also, due to the lower environmental air pressure at higher altitudes, the air pressure within the breathing system must be lower in order to inhale; in order to meet this requirement, the thoracic diaphragm lowers to a greater extent during inhalation, which in turn causes an increase in lung volume.

RESPIRATION AND LANGUAGE RESEARCH

Assessment of respiratory responses may be relevant for a broad variety of research areas, including studies of the physiological effects of mental load and stress, investigations of physiological correlates of emotions and affect, and research on speech planning and processing. It has been shown that linguistic planning relies on and is shaped by respiratory requirements and speaker's momentary respiratory state. A study conducted by Włodarczak and Heldner (2017) proposed a mechanism whereby respiratory patterns are determined by the trade-off between speakers' communicative goals and respiratory constraints showed that the coordination of speech and breathing conforms to the economy principle, and if the speaker has enough air in the lungs to satisfy the requirements of the upcoming utterance, it is produced on residual breath. However, when lung levels become too low for sustaining even a short vocalization, gestural feedback is preferred in place of verbal feedback, as evidenced by the fact that nods are more likely in the vicinity of inhalation onsets (Włodarczak & Heldner, 2017).

Research has also shown that speech planning is reflected in respiratory patterns, especially in read speech. For instance, the duration and amplitude of inhalation have been found to correlate positively with the upcoming utterance length in several studies (Fuchs, Petrone, Krivokapić, & Hoole, 2013; Winkworth, Davis, Adams, & Ellis, 1995). The location of inhalation is also strongly determined by speech planning. Almost all inhalations in read speech occur at major constituent boundaries, such as paragraphs, sentences, or phrases (Conrad, Thalacker, & Schönle, 1983; Grosjean & Collins, 1979).

By contrast, breathing in spontaneous speech shows a less consistent pattern. It has been claimed that as many as 13% of all inhalations in spontaneous monologues occur at grammatically inappropriate locations (Wang, Green, Nip, Kent, & Kent, 2010), possibly due to the additional demands of real-time speech planning. The effect should be even more pronounced in spontaneous conversation, where the communicative demands are different.

A key characteristic of the conversational rhythm is its oscillating pattern—generally, one speaker at a time has the speaking turn and simultaneous speech tends to be avoided. Thus, the exchange of speaker and listener roles is precisely coordinated by means of turn-taking cues indicating the intention to take, hold, or release the turn (McFarland, 2001). Breathing patterns have previously been hypothesized to be part of the turn-taking system. Inhalations have been claimed to be an interactionally salient cue to speech initiation (Schegloff, 1996) and to be deeper before turn initiation (Ishii, Otsuka, Kumano, & Yamato, 2014). Finally, breath holding and exhalation have been suggested as turn keeping and turn-yielding devices, respectively (French & Local, 1983).

Furthermore, durational properties of respiration have been shown to reflect turn-taking intentions. Speakers tend to minimize pause durations inside the turn by inhaling more quickly and by reducing the delay between inhalation offset and speech onset (Hammarsten et al., 2015; Rochet-Capellan & Fuchs, 2014). As inhalation duration and depth have been found to correlate, at least in read speech (Rochet-Capellan & Fuchs, 2013), the amplitude of non-initial inhalations in a speaking turn should also be smaller.

Previous research indicated that inhaling the approximate amount of air necessary for the upcoming utterance might not be the only purpose of the intake of breath. Inhalations in spontaneous speech might also mark the intention of claiming the conversational floor. Accordingly, the hypothesis under investigation here is that dialogue turns consisting of multiple breath groups should show that the turn-initiating inhalation is larger in amplitude than later inhalations within the turn.

Speech Breathing

Speech breathing commonly refers to the special manner of using the respiratory mechanisms to produce airflow for phonation. According to Euler (1982), speech production usually demands more effort than quiet breathing, and the system is optimized to provide the required airflow. During speech, the rate and volume of inhalation and rate of exhalations are mostly governed by the speech controlling system. For example, this system takes into account requirements for phrasing, loudness, and articulations. An important aspect distinguishing automatic or metabolic breathing from voluntary and controlled speech breathing is the brain structure responsible for these mechanisms (McKay, Evans, Frackowiak, & Corfield, 2003). The first is controlled primarily by the bulbopontine centers in the brainstem, whereas the second also involves cortical structures (Euler, 1982). The significance of this difference is that the cerebral cortex and other forehead structures control the respiratory system on a higher organizational level. As other speech functions are also controlled by the cerebral and cerebellar regions of the brain (Blank, Scott, Murphy, Warbuton, & Wise, 2002), this connects the organization of speech breathing to other aspects of speech production. Metabolic breathing, on the other hand, is part of the optimal gas-exchange system for life purposes (Euler, 1982).

Both the rib cage and abdomen can be used to displace air during speech. Some speakers exhibit the stronger use of rib cage over abdominal contributions, and some speakers show a relatively equal contribution from both the rib cage and the abdomen (Hixon, 1982). In general, the type of articulation involved, overall vocal effort, and the habits of the individual speaker have an effect on the aerodynamic demands of speech on the respiratory system (Clark et al., 2007).

According to Hixon (1987), speech breathing demands the necessary amount of alveolar pressure to ensure the steady production of utterances. Alveolar pressure is constant during both sustained utterances and conversational speech, but depends on several variables. For example, muscular pressure and relaxation pressure need to be balanced for alveolar pressure to stay constant. More specifically, at high lung volumes, a net inspiratory force is added to the relaxation pressure, but the magnitude of this force decreases as the amount of air in the lungs decreases during speech. At around half of the VC, the net force value is zero. Accordingly, when the level of air in the lungs falls below that, a positive muscular pressure needs to applied increasingly while the lung volume steadily decreases, but pressure needs to be maintained.

Although speech breathing demands more effort than normal quiet breathing, Clark et al. (2007) observe that both operate in the lower midrange of vital capacity and the minimum respiratory volumes at the end of the exhalation phase tend to be around 30%–40% of VC. However, the tidal peak after inhaling can range from 45% of VC in quiet breathing to 80% of VC in loud speech (Clark et al., 2007). According to Hixon (1982), conversational speech is normally encompassed around approximately 40%–60% of VC, while most utterances begin from around twice the resting TV and end just above FRC. Hixon, Goldman, and Mead (1973) have also compared read speech and conversations and found that regardless of the condition, in most utterances, speech was initiated at 50%–60% VC and terminated at approximately 30%–50% of VC in the upright position, while a typical speech breathing exhalation phase had the amplitude of approximately 10%–20% of VC, in some cases reaching 30% of VC. Occasionally, speech ends even lower, in the expiratory reserve level, because speakers aim to finish utterances without inspiratory interruption.

Hixon (1987) described the differences between the quiet and speech breathing cycles, and he explains that while the quiet breathing cycle may repeat twelve or more cycles per minute with exhalations lasting slightly longer than inhalations, the frequency of inhalations and exhalations in speech breathing is lower. The relative durations of the phases change because inhalations become considerably shorter than exhalations to minimize interruptions to the speech flow. Exhalations, on the other hand, become much longer due to higher resistances in the upper airway that prevent air from quickly flowing out. Therefore, the patterns of quiet breathing and speech breathing are very different: quiet breathing encompasses relatively equal phases of inhalation and exhalation in terms of duration, amplitude, and velocity, whereas speech breathing is characterized by short inhalations and long exhalations. Hixon (1987) points out that the hallmark of the volume changes of conversational speech is in fact the irregularity of the breathing cycle.

Speech Planning

The three phases of speech production are respiration, phonation, and articulation. As the driving force of the speech, respiration plays a very important role in the process of planning and producing speech. It is generally agreed that language production is incremental (e.g., Kempen & Hoenkamp, 1987) as during language processing, one level of information triggers activity on the next level of the production system. In a simplified manner, it is the piece-by-piece process that guides an idea or thought all the way to articulation and thus results in language and speech production, corresponding to specific communicative demands (Ferreira & Swets, 2002). However, it is not completely clear how incremental language production exactly is. Some studies suggest that it is radically incremental in that speakers start articulating when they know the first word of their utterance and during that, the planning of the next phonological word takes place (Levelt, 1989; Wheeldon & Lahiri, 1997). Others have found evidence that language planning can be more flexible and speakers tend to look for balance between planning and initiating speech quickly, indicating that people are capable of planning larger portions of the utterance beyond the immediate phonological word (Ferreira & Swets, 2002). That can be exemplified by the use of common expressions, collocations, or idioms that tend to form single fixed units in the speakers' processing memory as opposed to being simply strings of words (Wray & Perkins, 2000).

Much of the system for speech planning and organization has been studied by comparing the proportions and timing of speech and pausing. Pauses in speech have been claimed to be controlled by different variables, such as the rate of speaking, syntactic strength of boundaries, emphatic stress, sentence length, and so on. According to Cruttenden (1986), pauses occur at either major constituent boundaries, before words of high lexical content, or after the first word in an intonation group, while the last two types are interpreted as hesitation pauses (Cruttenden, 1986). Butterworth (1975) examines how strongly pause locations correspond to phonemic clause boundaries and suggests that speakers plan ahead in terms of clauses and sentences, but they also have the ability to plan superordinate units consisting of multiple clauses and sentences that form a kind of semantic unit. A study conducted by Krivokapić (2010) examined prosodic phrase length effects on pause durations in read English, showing that speech is planned quite far ahead beyond the extent of the first phrase but the exact extent depends on the particular speaker. In addition, Butterworth has pointed out that some pauses could have the communicative function of helping the listener segment the speech (Butterworth, 1975). Therefore, pauses not only have the purpose of providing time for cognitive processing to formulate speech but also help guide the listener's interpretation as well.

Respiratory patterns occurring during read speech have been investigated extensively and a number of respiratory variables connected to speech planning have been looked at closely. Analysis on reading texts has concluded that almost 100% of inhalations occur at syntactic boundaries marked with punctuation or conjunctions (Rochet-Capellan & Fuchs, 2013). More precisely, it has been determined that in read speech, speakers always inhale between paragraphs, very likely inhale between sentences and sometimes also in complex sentences before a comma or connectors (Conrad et al., 1983). Remarkably, even reading tasks where speakers are asked to produce only silent, inner speech result in a speech-like respiratory pattern, indicating that breathing is controlled by the cortical structures even when speech is not actually articulated (Conrad & Schönle, 1979). A study conducted by

Fuchs et al. (2013) with read German identifies a series of respiratory patterns connected to the syntactic content of the text. They conclude that longer and deeper pauses lead to longer sentences, but syntactic complexity does not indicate the same necessity and instead causes more frequent inhalations as compensation (Fuchs et al., 2013). Whalen and Kinsella-Shaw (1997) demonstrate a similar effect of utterance length (in terms of durational and syllabic length) on inhalation duration, regardless of whether inhalations were measured acoustically or physiologically. Grosjean and Collins (1979) also investigated the syntactic nature of breathing pauses and set speech rate as a variable. They discovered that at slow and normal rates, speakers prefer to inhale at major constituent breaks, but when the rate is increased, there are fewer breathing pauses and they occur whenever speakers have the need for air. This is caused by the speakers' wish to minimize the number of pauses and maximize the speech rate by inhaling very quickly and only when absolutely necessary (Grosjean & Collins, 1979). Hixon et al. (1973) report similar behavior from an experiment where speakers were asked to read long sentences at lower lung volumes. They conclude that in those cases, the mechanical aspects of breathing become more important than speech phrasing. According to this study, low levels of air forced the speakers to inhale at unconventional locations in the reading passage to attend to the system's demands in order to continue the utterance.

On the other hand, spontaneous speech is less predictable than reading because speakers do not have a prepared text to check before producing utterances. Differences in respiratory patterns between read and spontaneous speech have been explored by Winkworth et al. (1995), who investigated whether the associations between linguistic factors and lung volumes in read speech also hold in spontaneous speech. They conclude that the location of inhalations followed clause structure in 72 percent of the cases and that longer breath groups have a higher initiation lung volume than short breath groups. The term "breath group" itself was introduced to denote the boundaries of a prosodic pattern of simple declarative sentences in normal speech, mainly defined by the fact that they are uttered on a single exhalation (Lieberman, 1967). Findings on inhalation locations indicate that speech is mostly structured into breath groups taking into account not only respiratory demands but also grammatical structure, and, as such, breath groups tend to consist of relatively complete clauses, phrases, or sentences. Indeed, grammatically inappropriate inhalations have been found to occur around 2% for reading and 13% for spontaneous speech in English (Wang et al., 2010). However, Winkworth et al. (1995) claim that there is large individual variation to these numbers and that in spontaneous speech, breath groups rather reflect units of meaning (Winkworth et al., 1995). Rochet-Capellan and Fuchs (2013) investigated spontaneous German in terms of how inhalation depth and duration were connected to syntactic contents of breath groups. Their results show that both the amplitude and the duration of inhalation depend on the length of the following breath group, but also whether it started with a matrix clause or some other clause type. If the breath group started with a matrix clause, the preceding inhalation was deeper. In addition, inhalations were found to be deeper when the breath groups contained at least one hesitation.

The Respiration Pattern during Turn Organization

Spontaneous speech usually occurs in the form of a conversation between two or more interlocutors. Conversation, as defined by Jaffe and Feldstein (1970), is a sequence of sounds and silences generated by two or more interacting speakers (Jaffe & Feldstein, 1970). A key feature of conversational rhythm is its oscillating pattern—one speaker at a time has the speaking turn and simultaneous speech is generally avoided (Jaffe & Feldstein, 1970). Therefore, conversational exchange requires precisely coordinated collaboration in the form of turn-taking movements between the partners—one speaker, who holds the floor, while the other(s) are listener(s) (McFarland, 2001). Most studies on spontaneous speech involve two speakers, who exchange turns. Although an undeniably useful source of data for studying mechanisms of turn exchange, the mechanisms used to organize turn-taking become more complicated in multiparty conversations. There are a number of intricate strategies for claiming the conversational floor, even though speakers might not be aware of using these devices. Some strategies are used in order to claim the floor, others to keep the floor by avoiding interruptions, and a third type of devices to hand over the speaking turn to another participant. The signals guiding conversational interpretation are said to be empirically detectable as interactional intentions need to be clearly identifiable during conversations (Gumperz, 1982). Listeners are known to turn their attention to stimuli which seem relevant for processing, and, as such, these must be communicated as relevant by the speaker (Wharton, 2009). Turn-taking events such as a speaker switch, where one person loses the possession of the floor and another person gains it (Jaffe & Feldstein, 1970), can be achieved by using certain turn organizational cues or a combination of them.

The turns speakers take are usually defined as *turn-constructional units*, which can be various unit-types like sentential, clausal, or lexical constructions speakers use to construct a turn (Sacks, Schegloff, & Jefferson, 1974). Feldstein (1973), however, has used the term *utterance* when determining turn-taking events. According to him, an utterance is made up of sequences of pauses and vocalizations of one speaker that are bounded by switching pauses, where a speaker switch occurs, or vocalizations by other speakers at both ends (Feldstein, 1973). The borders of turn-constructional units or utterances can be intensified with the help of a number of prosodic markers, for example, intonation, stress, intensity, voice quality, and the rhythm of phrasing, or pausing and speaking. The extent and manner of use for each feature depends on what the speaker wishes to convey and is affected by the incremental nature of speech: the prosodic content of an utterance is created continuously by moment-to-moment decisions about if and how to continue (Couper-Kuhlen & Selting, 1996). For example, if the final accented syllable of an utterance in German is said on a mid-level pitch, it is perceived as incomplete, whereas a lowering pitch at the same location would demonstrate the ending of an utterance (Selting, 1995). This is connected to declination—a phenomenon whereby pitch lowers during an intonation group due to a decline in transglottal pressure caused by using up the air in the lungs (Cruttenden, 1986). As such, falling intonation usually signals the end of a sentence or utterance in many of the world's languages. Another connection here can be made to voice quality: modal voice at the end of an utterance tends to signal incompleteness while irregular phonation or creakiness has been reported to be a phrase-end or turn-end marker due to very low fundamental frequency accompanying it (Slifka, 2007). For example, creaky voice as a turn-ending marker is used in Finnish (Ogden, 2001), Swedish (Carlson, Hirschberg, & Swerts, 2005), English Received Pronunciation (Laver, 1994), American English when combined with yeah (Grivičić & Nilep, 2004), but curiously not so clearly in Estonian (Aare, Lippus, & Šimko, 2014). When a speaker's voice becomes creaky, it can be therefore interpreted as a signal that they have exhausted the air in their lungs and need to inhale soon, providing a convenient location for taking over the conversational floor.

Cues important for the organization of conversational dynamics can also be inferred from visual signals. The devices people use include gestures, eye-gaze, and facial expressions, all of which contribute to the interpretation of speaker and/or listener intentions in conversation. The loss of visual-gestural cues, as happens in phone conversations, has been reported to alter the temporal patterns of interaction: pause durations and stretches of simultaneous speech become shorter (Jaffe & Feldstein, 1970). The purpose of spontaneous movements that accompany speech is claimed to constrain the inferential process by triggering a variety of emotion or attitudinal concepts, and altering the salience of linguistically possible alternatives (Wharton, 2009). According to Bavelas et al. (1995), such interactive gestures can coordinate speaking turns. In fact, they propose that speakers can gesturally take the turn, give away the turn, or indicate the floor is free for taking. They also suggest that the words and gestures in spontaneous dialogues are not separate channels but function as a whole.

Respiratory activity during speech can be both visible and audible. Schegloff (1996) has suggested that an audible inhalation functions as a pre-beginning element in turn-taking and projects the onset of talk (Schegloff, 1996). It is also known that breath holding can function as a marker of turn incompleteness and exhaling can be a turn-yielding device (Edlund, Heldner, & Włodarczak, 2014; French & Local, 1983). Before initiating speech, inhalations can be produced with a strong frication or by inhaling in a way that extensively stretches the rib cage to show the intention of speaking with body language. For example, pre-speech inhalatory noise has been found to be audible before short sentences, but single words are usually preceded by silence (Scobbie, Schaeffler, & Mennen, 2011). In addition, research has shown that breathing adapts to dialogue turns and there is some evidence for interpersonal coordination of breathing in turn-taking at a global level (Rochet-Capellan & Fuchs, 2014). Rochet-Capellan and Fuchs (2014) have also looked more closely at how breathing cycles might adapt to dialogue events. Their analysis shows that in order to hold a turn, speakers reduced inhalation durations compared to those coinciding with speaker change and thus preserved their turn. They also explain that breathing profiles are different depending on whether speakers are trying to claim the turn or if they are holding the turn: in general, respiratory cycles in turn-taking were longer than in turn-holding and therefore, the breathing pattern of turn-holding was more asymmetrical than for turn-taking. Furthermore, their data on spontaneous German speech demonstrated that turn-taking was more successful after a new inhalation, indicating that speakers coordinate their breathing with turn-taking. (Rochet-Capellan & Fuchs, 2014). McFarland (2001) investigated the possible influence of turn-taking on respiratory kinematics by comparing the mean inhalatory and exhalatory durations for three breathing cycles directly before and after the onset of speech in scripted dialogues. His results did not reveal significant influence of upcoming speech to the inhalation duration. However, after the onset of speech, the first inhalation was significantly longer than the following two, which in turn were comparable in duration (McFarland, 2001).

By contrast, some contributions to spontaneous conversations do not need to be planned. An example of this is the occurrence of backchannels (Yngve, 1970), which are short unplanned listener responses indicating that the listener is understanding and following the speaker (Heldner, Hjalmarsson, & Edlund, 2013). Due to the relative unpredictability of backchannels and laughter, they are generally regarded as non-interruptive and not considered as attempts to claim the conversational floor (Heldner et al., 2013). As research has shown, vocalized backchannels tend to occur around speaker's exhalation offset in the listener's respiratory cycle, and are often located near the onset of listener's inhalation phase. Occasionally, backchannels also occur in the inhalation phase of the listener and could, in theory, be located almost everywhere in the listener's breathing cycle (Aare, Włodarczak, &

Heldner, 2014). Recent research has also provided evidence that backchannels and other very short utterances, such as short answers to questions (Torreira, Bögels, & Levinson, 2015), can be produced on residual air. After taking into account the respiratory needs for the upcoming utterance, speakers can choose not to inhale if they already have enough air in their lungs to be able to produce the entire utterance (Włodarczak & Heldner, 2015).

All of these markers are combined with the syntactic content of utterances and help determine the turn-taking intentions of participants. From a practical point of view, the results from studies on speech respiration provide information for applications like human information processing in human-computer interactions. For example, Ishii et al. (2014) have investigated how to predict the next speaker in a multiparty conversation based on the participants' respiratory patterns. They observed that the person who wants to hold the floor inhales more quickly and with a larger amplitude than the subsequent listeners and that the new speaker takes a bigger breath than listeners in a turn-changing event (Ishii et al., 2014). Similarly, it is known that in a question-answer situation, short replies are mostly produced on residual breath, whereas longer responses are preceded by an inhalation (Torreira et al., 2015) which can be audible and could help narrow down the possible sequential alternatives in conversations.

IMPORTANT CONSIDERATIONS ABOUT METHODOLOGICAL PROCEDURES

Standard Recording Devices

Respiration (RSP) can be recorded by measuring abdominal or thoracic expansion and contraction while breathing. Timing and volume components of respiration can be measured by a variety of techniques. These range from relatively intrusive techniques such as *spirometry* and *pneumotachography* to indirect measurement of respiratory parameters by means of bands or strain gauges on the torso. Although they provide very accurate assessment of the timing and volume components of the breathing cycle, the major disadvantage of intrusive techniques is that they typically employ equipment that adds dead space and resistance to breathing (e.g., mouth piece, facemask or tubes with valves). For this reason, measurement of the movement of the chest is a better alternative.

Spirometry

Spirometry (meaning the measuring of breath) is the most common of the pulmonary function tests. It measures lung function, specifically how much air is inhaled, how much air is exhaled, and how quickly air is exhaled. To take a spirometry test, you sit and breathe into a small machine called a spirometer. This test can trigger dizziness or shortness of breath, and it requires some exertion; therefore, it is not recommended for experimental conditions of social behavior.

Pneumotachography

Pneumotachography accurately and quantitatively measures airflow volume. In awake subjects, pneumotachography is known to alter breathing by increasing TV and reducing respiratory rate. Several types of pneumotachographs are available, and these devices differ with respect to measurement technique. They use either differential pressure airflow transducers (the most widely used), ultrasonic flow meters, or hot-wire anemometers (Hirshkowitz & Kryger, 2017). These devices usually require that the participant wear a face mask, and the procedure can be uncomfortable; therefore, pneumotachography is not commonly used for research of social and linguistic behavior.

Respiratory Inductance Plethysmography

Although the pneumotachometer is currently the most accepted device to measure tidal breathing, it requires the use of a mouthpiece, and thus it induces the alteration of spontaneous ventilation. Respiratory inductive plethysmography, on the other hand, is able to determine spontaneous tidal breathing without the use of a facemask or mouthpiece. Respiratory inductive plethysmography includes two belts: one thoracic and one abdominal.

Structured Light Plethysmography

Structured light plethysmography (SLP) is a noncontact, noninvasive, respiratory measurement technique, which uses a structured pattern of light and two cameras to externally track displacement of the thoraco-abdominal wall during tidal breathing.

Dual Band Respiration

Several studies have examined this two-degrees-of-freedom model of chest wall motion, in which ventilation can be derived from measurements of rib cage and abdomen displacements. With this model, TV is calculated as the sum of the anteroposterior dimensions of the rib cage and abdomen, and could be measured to within 10% of actual Vt as long as a given posture was maintained.

Single Band Respiration

With this approach, changes in volume of the thoracic cavity can also be inferred from displacements of the rib cage and diaphragm. Motion of the rib cage can be directly assessed, whereas the motion of the diaphragm is indirectly assessed as the outward movement of the anterolateral abdominal wall. However, accuracy issues arise when trying to assess accurate respiratory volumes from a single respiration band placed either at the thorax, abdomen or midline. Due to differences in posture and thoraco-abdominal respiratory synchronization, it is not possible to obtain accurate respiratory volumes with a single band.

The Biopac Respiratory Effort Transducer SS5LB and the Respiration Transducer BN-RESP-XDCR

One example of a single band respiration recording device that can be used to measure abdominal or thoracic expansion to record respiratory effort is the Biopac *Respiratory Effort Transducer SS5LB*. If the researcher needs a wireless setup, Biopac offers the BioNomadix line's *Respiration Transducer BN-RESP-XDCR*. This transducer connects to an RSP transmitter (e.g., BN-RSP2 or BN-RSPEC) to measure changes in thoracic or abdominal circumference that occur as a subject breathes with a single band (see figure 9.1). Biopac claims that either design presents minimal resistance to movement and that both are extremely unobtrusive. Biopac's transducers can measure

Figure 9.1 The Placement of a Respiration Belt Transducer. *Source*: Image courtesy of Biopac.

slow to very fast respiration patterns with no loss in signal amplitude, while maintaining good linearity and minimal hysteresis.

Recommendations for Data Collection

The ideal protocol for data collection will largely depend on the goal of the study. Therefore, it is recommended that the researcher becomes familiar with the literature that uses respiration as a measure of autonomic regulation in linguistic performance to get informed about best practices and standards.

Having said that, a good example of a study that provides detailed information about their own data collection protocol for respiration measures is one conducted by Aare (2015). In this study, participants were instructed to wear tight-fitting clothes to maximize accuracy of the respiratory signals. Respiratory activity was measured with *respiratory inductance plethysmography*, which quantifies changes in the rib cage and abdominal cross-sectional area with the use of two elastic transducer belts (Ambu RIP-mate) placed on two levels: one at the level of the armpits and the other on the level of the navel. Both belts were connected to specially developed respiratory belt processors (RespTrack), designed and built in the Phonetics Laboratory at Stockholm University (see Edlund, Heldner, & Włodarczak, 2014); they were optimized for low noise and low inference recordings of respiratory movements in speech and singing. The signals from the rib cage and abdomen were weighted with a potentiometer which allows for calibration producing a sum signal estimating total lung volume change. All three described tasks and the respiratory signal during the task were recorded with *LabChart* software and *PowerLab* hardware (ADInstruments).

Placement of the Respiration Transducer Belt

The researcher should first ask the participant if they breathe primarily through their stomach or chest area so that the respiration belt is placed accordingly to maximize sensitivity. Then the researcher should ask the participant to exhale completely, then tighten the respiration belt around their abdomen/chest area. The researcher should make sure that the belt is not in any way loose around the participant's body at the point of complete exhalation.

Baselines

Participants should be asked to perform two respiratory maneuvers to measure their resting expiratory level and their VC. For the first, the speakers inhale some air and then exhale it without applying any force from their abdominal muscles, until they reach the relaxation level. For the second, they are asked to inhale to the TLC and exhale until reaching the RV, while standing straight.

These measurements are necessary for determining the minimum and maximum values of the lung volumes under the speakers' conscious control.

Artifacts

During measurement of respiration, two sources of artifacts may be encountered that have to be dealt with: speech and movement. The influence of speech upon the morphology of the breathing cycle is reflected on the irregular expiratory movement of air through the glottis that is typical of voice production. However, analysis of the respiratory signal during speech in terms of volume and time components is notoriously difficult. Therefore, it is important to avoid movements caused by speech during the measurements—at least for baseline recordings. During other tasks, the experimenter should take measures to restrict participants' movements, like asking them to keep their feet flat on the floor and hands flat on a table or desk.

Task Setup for One or More Participants

The recording of the respiration pattern for one participant is relatively the same as the setup for two or more participants. However, the researcher must make sure to have enough microphones and cameras pointed at each of the participants in a group task. The audio signal of the conversation task can be recorded with head-worn microphones using a cardioid polar pattern (e.g., Sennheiser HSP 4) in software like *LabChart* for synchronization with respiratory signals, and using *Reaper* software (Cockos Incorporated, 2014) for high-quality sound. The speakers should be asked to stand in a circle around a 1-meter high table for the entire calibration process and recording, keeping their hands placed on the table's surface during the experiment to minimize body movements. The participants should be recorded in video for the researcher to be able to check possible movements if the respiratory signals show artifacts or otherwise obscure patterns. Each speaker should be assigned a specific place to stand at, facing a camera placed in such manner that it is capable of recording the participant's every move from the head to the elbows. It is recommended to place one separate camera for each participant if one camera can't record all of them.

Recommendations for Data Processing

Removal of Artifacts

Determining whether an apparent abnormality in the respiration record is physiological in nature or not requires additional information about the task and participants' movements during the measurement. A synchronized video recording of the subject can help in the identification of artifacts like subject movement and talking. For example, if using Biopac recorders, the researcher can use their software *AcqKnowledge* to sync video with data in order to have a visual recording that is perfectly synced with the data. The experimenter could also manually enter markers in the data during the experiment whenever the subject moves, talks, and does other activities.

Confirm That the Respiration Rate Calculation Is Correct

Normal respiration rate is between 6 and 20 breaths per minute (BPM). If there is an unusual change in respiration rate, it can be calculated manually to verify the accuracy of the rate calculation. To calculate respiration rate manually, highlight the interval from one respiration cycle to the next in your data and set one of the measurement boxes to BPM.

Chapter 10

Facial Expression Analysis

A BRIEF OVERVIEW OF FACIAL EXPRESSION ANALYSIS

Facial expression analysis goes well back into the nineteenth century. Darwin demonstrated already in 1872 the universality of facial expressions and their continuity in man and animals and claimed, among other things, that there are specific inborn emotions, which originated in serviceable associated habits. Darwin's ideas about emotions were a centerpiece of his theory of evolution, suggesting that emotions and their expressions were biologically innate and evolutionarily adaptive and that similarities in them could be seen phylogenetically. A century later, Paul Ekman and Carroll Izard conducted *universality studies*, and they were able to demonstrate that there is a high cross-cultural agreement in judgments of emotions in faces by people in both literate (Ekman, 1972; Ekman & Friesen, 1971; Ekman, Sorenson, & Friesen, 1969; Izard, 1971) and preliterate cultures (Ekman & Friesen, 1971; Ekman et al., 1969).

In 1971, Ekman and Friesen (1971) postulated six basic emotions that possess each a distinctive content together with a unique facial expression. In the past, facial expression analysis was primarily a research subject for psychologists, but already in 1978, Suwa et al. (1978) presented a preliminary investigation on automatic facial expression analysis from an image sequence. In the 1990s, automatic facial expression analysis research gained much interest starting with the pioneering work of Mase and Pentland (1991). The reasons for this renewed interest in facial expressions were mainly due to advancements accomplished in related research areas such as face detection, face tracking, and face recognition, in addition to the recent availability of growingly cheap computational power. Various applications using automatic facial expression analysis can be envisaged in the near future, fostering further interest in doing research in different areas, including image understanding, psychological studies, video-indexing, robotics as well as virtual reality.

Facial expression recognition should not be confused with human emotion recognition. While facial expression recognition deals with the classification of facial motion and facial feature deformation into abstract classes that are purely based on visual information, human emotions are a result of many different factors, which can be determined through a number of other variables such as emotional voice, pose, gestures, gaze direction, in addition to facial expressions. Furthermore, emotions are not the only source of facial expressions. In contrast to facial expression recognition, emotion recognition is an interpretation attempt and often demands understanding of a given situation, together with the availability of full contextual information.

One of the most informative sources of information about others' emotions is their faces. We can read other people's faces based on changes in key features such as eyes, lids, brows, nostrils, and lips. Maintenance of social interactions requires constant decoding of other people's facial expressions, and this ability is a central component of competent communication skills. Information obtained from another person's facial expressions are paired with cues from voice intonation and pitch, posture, gestures, gaze direction, among other variables in order to obtain a more complete best-guess reading of their emotional state (see figure 10.1).

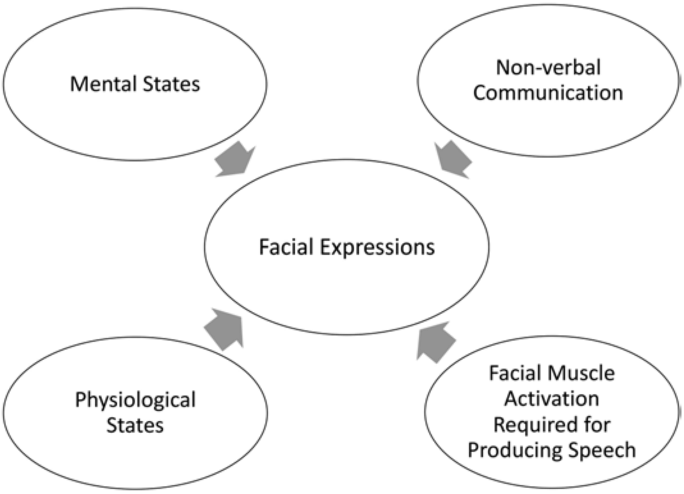

Figure 10.1 Underlying Variables Modulating Facial Expressions. Facial Expressions Can Be the Result of Several Factors, Such as Mental States, Physiological States, Nonverbal Communication, and the Use of Facial Muscles Required for the Production of Speech. *Source*: Diagram created by author.

The human face comprises over 40 structurally and functionally autonomous muscles, each of which can be triggered independently of each other. The facial muscular system is the only place in our body where muscles are attached either to a bone *and* facial tissue (other muscles in the human body connect to two bones) or only to a facial tissue such as the muscle surrounding the eyes or lips.

The facial muscles are a group of striated skeletal muscles that are supplied by the facial nerve (cranial nerve VII). The nearby masticatory muscles are supplied by the mandibular nerve, a branch of the trigeminal nerve (cranial nerve V). The eyes are supplied by the trochlear nerve (cranial verve IV), oculomotor nerve (cranial nerve III), and the optic nerve (cranial nerve II). These nerves are part of the social engagement system (Porges, 2007, 20011a, 2011b), comprised of muscles and organs that subserve social behavior; they are the vestibulocochlear nerve, involved in hearing and balance (cranial nerve VIII); the glossopharyngeal nerve (cranial nerve IX), which supplies the pharynx, middle ear, posterior one-third of the tongue; and the vagus nerve (cranial nerve X), which interfaces with the parasympathetic control of the heart, lungs, and digestive tract and has a sympathetic function via the peripheral chemoreceptors.

Facial Expression Measurement

Facial expressions are generated by contractions of facial muscles, which results in temporally deformed facial features such as eye lids, eye brows, nose, lips, and skin texture, often revealed by wrinkles and bulges. Typical changes of muscular activities are brief, lasting for a few seconds, but rarely more than 5s or less than 250ms (Fasel & Luettin, 2003). Of particular importance is the location of facial actions, their intensity as well as their dynamics. Facial expression intensities may be measured by determining either the geometric deformation of facial features or the density of wrinkles appearing in certain face regions. For example, the degree of intensity of a smile is communicated by the magnitude of cheek and lip corner raising as well as wrinkle displays (Messinger & Fogel, 1999). Since there are interpersonal variations with regard to the amplitudes of facial actions, it is difficult to determine absolute facial expression intensities without referring to the neutral face of a given person. Note that the intensity measurement of spontaneous facial expressions is more difficult in comparison to posed facial expressions, which are usually displayed with an exaggerated intensity and because of that it be identified more easily.

Not only the nature of the deformation of facial features conveys meaning but also the relative timing of facial actions as well as their temporal evolution. Static images do not clearly reveal subtle changes in faces and it is therefore essential to measure also the dynamics of facial expressions. Facial expressions can be described with the aid of three temporal parameters: onset (attack), apex (sustain), and offset (relaxation). These can be obtained from human coders, but often lack precision. Few studies relate to the problem of automatically computing the onset and offset of facial expressions, especially when not relying on intruding approaches such as facial EMG. There are two main methodological approaches of how to measure the aforementioned three characteristics of facial expressions, namely *message judgment-based* and *sign vehicle–based* approaches (Ekman, 1982). The former directly associate specific facial patterns with mental activities, while the latter represent facial actions in a coded way, prior to eventual interpretation attempts.

Judgment-Based Approaches

Judgment-based approaches are centered around the messages conveyed by facial expressions. When classifying facial expressions into a predefined number of emotion or mental activity categories, an agreement of a group of coders is taken as ground truth, usually by computing the average of the responses of either experts or nonexperts. Most automatic facial expression analysis approaches found in the literature attempt to directly map facial expressions into one of the basic emotion classes introduced by Ekman and Friesen (1971).

Sign Vehicle–Based Approaches

With sign vehicle–based approaches, facial motion and deformation are coded into visual classes. Facial actions are hereby abstracted and described by their location and intensity. Hence, a complete description framework would ideally contain all possible perceptible changes that may occur on a face. This is the goal of facial action coding system (FACS), which was developed by Ekman and Friesen (1978) and has been considered as a foundation for describing facial expressions. It is appearance-based and thus does not convey any information about the mental activities associated with expressions. FACS uses forty-four action units (AUs) for the description of facial actions with regard to their location as well as their intensity, the latter either with three or five levels of magnitude. Individual expressions may be modeled by single AUs or AUs combinations. Similar coding schemes are the EMFACS (Friesen & Ekman, 1984), MAX (Izard, 1979), and AFFEX (Izard, Dougherty, & Hembree, 1983). However, these approaches are only directed toward emotions. Finally an alternative that encompasses analysis, coding, and animation of faces (talking heads) is the MPEG-4-SNHC (Koenen, 2000). Instead of describing facial actions only with the aid of purely descriptive AUs, scores of sign-based approaches may be interpreted by employing facial expression dictionaries. Friesen and Ekman introduced such a dictionary for the FACS framework (Friesen & Ekman, 1987). Ekman et al. (1998) presented a database called facial action coding system affect interpretation database (FACSAID), which allows a researcher to translate emotion-related FACS scores into affective meanings. Emotion interpretations were provided by several experts, but only the agreed affects were included in the database.

Voluntary and Involuntary Facial Expressions

Facial expressions can be voluntarily or involuntarily made, and the neural mechanisms responsible for controlling either expression differ in each case. While voluntary facial expressions are often socially conditioned and follow a cortical route in the brain, involuntary facial expressions are believed to be innate and follow a subcortical route. Voluntary facial expression originated in the primary motor cortex and travel through the pyramidal tract, specifically the corticobulbar projections. The primary motor cortex is associated with displays in emotion, which are social precepts that influence and modify expressions. On the other hand, involuntary facial expressions originate from the extrapyramidal motor system, which involves subcortical nuclei. This kind of expression is demonstrated in infants before the age of two; they can display distress, disgust, interest, anger, contempt, surprise, and fear. Infants' displays of these emotions indicate that they are not cortically related. In addition, blind children also display emotions, proving that they are subconscious rather than learned. Other subcortical facial expressions include the *knit brow* during concentration, raised eyebrows when listening attentively, and short *punctuation* expressions to add emphasis during speech. People can be unaware that they are producing these expressions.

The brainstem controls involuntary and unconscious facial expressions that occur spontaneously, whereas the motor cortex is involved in consciously controlled and intentional facial expressions.

Macroexpressions and Microexpressions

When single emotions occur and there is no reason for them to be modified or concealed, expressions typically last between 0.5 to 4 seconds and involve the entire face (Ekman, 2003). These are called *macroexpressions* and are easily observed. Microexpressions, on the other hand, are expressions that are displayed in a fraction of a second, sometimes as fast as 1/30 of a second. They are so fast that if one blinks, they would miss them. Microexpressions are typically signs of concealed emotions but can also be signs of rapidly processed unconcealed emotional states. They occur so fast that most people cannot see or recognize them in real time. They can be more easily studied by replaying recorded video data.

Findings concerning the universality of facial expressions of emotion and the existence of microexpressions can help people in a range of professions requiring face-to-face interactions improve their skills in reading the emotions of others. Reading facial expressions of emotion, and especially microexpressions, can aid the development of rapport, trust, and collegiality; they can be useful in making credibility assessments, evaluating truthfulness and detecting deception; and better information about emotional states provides the basis for better cooperation, negotiation, or sales. Health professionals can develop better rapport with patients, interact humanely with empathy and compassion, and make the right diagnosis by obtaining complete information. Teachers can read the emotions of their students to obtain cues about the progress of their lesson plans so they can adjust accordingly and deliver them more effectively. School administrators who read the emotions of their teachers can reduce burnout and maintain and improve teacher effectiveness. Businesspersons and negotiators who can read the emotions of others can nurture mutually beneficial collaborations. Product researchers can improve the qualitative data they obtain from consumers by reading consumer’s emotions when evaluating products, giving hints as to what they truly feel despite what they say about it. Parents, spouses, friends, and everyone with an interest in building strong and constructive relationships can benefit from improving their ability to read emotions.

Automated Facial Expression Analysis

The physiognomies of faces vary from one individual to another quite considerably due to different age, ethnicity, gender, facial hair, cosmetic products, and occluding objects such as glasses and hair. Furthermore, faces appear disparate because of pose and lighting changes. Variations such as these have to be addressed at different stages of an automatic facial expression analysis system, namely face acquisition, feature extraction and representation, deformation extraction, motion extraction, and classification.

Face Acquisition

Ideally, a face acquisition stage features an automatic face detector that allows to locate faces in complex scenes with cluttered backgrounds. Certain face analysis methods need the exact position of the face in order to extract facial features of interest while others work, if only the coarse location of the face is available. Successful face acquisition depends on optimal pose (angle of the face and distance) and illumination.

Feature Extraction and Representation

Feature extraction methods can be categorized according to whether they focus on motion or deformation of faces and facial features, respectively, and whether they act locally or holistically.

Deformation Extraction

Deformation of facial features are characterized by shape and texture changes and lead to high spatial gradients that are good indicators for facial actions and may be analyzed either in the image or the spatial frequency domain.

Motion Extraction

The motion extraction methods that have been used for the task of facial expression analysis are dense optical flow, feature point tracking, and difference images. Dense optical flow attempts to compute the optical flow vector for every pixel of each frame. While such computation may be slower, it gives a more accurate result and a denser result suitable for facial expression analysis. Feature point tracking consists of detecting images of particles in a digital video sequence and linking these detections over time to follow the traces of such individual particles. Image differencing is an image processing technique used to determine changes between images. The difference between two images is calculated by finding the difference between each pixel in each image and generating an image based on the result.

Classification

Feature classification is performed in the last stage of an automatic facial expression analysis system. This can be achieved by either attempting facial expression recognition using sign-based facial action coding schemes or interpretation in combination with judgment or sign/dictionary-based frameworks. We can distinguish spatial and spatiotemporal classifier approaches.

FACIAL EXPRESSION ANALYSIS AND LANGUAGE RESEARCH

Social interactions often involve a complex interplay of speech and nonverbal cues displayed through face and body movements. During a dyadic interaction, up to 65% of the communication occurs through nonverbal channels (Knapp, 1996). While speech is the most direct communication channel for conveying messages during conversation, we effortlessly perceive and combine facial, head, body, and hand movements, among many other nonverbal cues, to provide a context within which speech is interpreted. Nearly 72% of the information conveyed nonverbally will take place on the face and body of an interaction partner (Knapp, 1996). Despite the importance of nonverbal cues to interpersonal communication, an increasing amount of everyday socialization occurs through email, social media, and video games that do not provide the same depth of interaction.

A study conducted by Svetleff and Anwar (2017) looked at how adult second language learners make use of their semiotic resources in their native and target languages while engaging in an unfamiliar task of storytelling and attempting to maintain self-regulation within two culturally and linguistically different contexts. Their findings indicated that second language speakers expressed more both positive and negative emotions while narrating a story in the target language, and maintained a “neutral” facial expression while narrating the same story in the native language, compared to when using their native languages. Another study conducted by Bala, McDaniel, and Panchanathan (2014) explored a computer interface that augments social interactions by conveying facial expressions through a haptic interface. They investigated the design of spatiotemporal vibrotactile patterns that map visual facial AUs to the tactile modality toward enriching social interactions that occur without direct access to the nonverbal cues displayed by another person. Though the proposed technology can be used to augment any social interaction occurring without the visual feedback of an interaction partner’s expressions and gestures, the proposed technology can have the potential social impact of improving the process of adjusting to blindness or visual disabilities. The authors added that individuals who are blind or visually impaired frequently encounter difficulties in social settings due to largely inaccessible visual social cues such as facial expressions and body language. Limited to no access to nonverbal communication channels can result in miscommunications and social awkwardness, which can then lead to social avoidance and isolation for many individuals who are blind. Assistive technologies have the potential to provide access to nonverbal social cues and social feedback for those who are visually impaired. Another study conducted by Jindal-Snape (2004) examined the role of feedback and self-evaluation in the growth of children with visual disabilities. The perception of visual social cues allows children to understand and incorporate norms of social interaction into their own mannerisms. Without this crucial visual feedback during their development, children with visual disabilities are often faced with issues related to social isolation and abnormal psychological development.

Today, most facial expression analysis systems are of the unimodal type, as they focus only on facial expressions when determining mental activities. However, the evaluation of multiple communication channels may foster robustness as well as improve correct interpretation of facial expressions in ambiguous situations. At present, most attempts of channel fusion are of the bimodal type and integrate voice in addition to facial expressions. Vocal expressions are conveyed by prosodic features, which include the fundamental frequency, intensity, and rhythm of the voice. Finally, facial expression recognition may be improved by considering not only facial actions but also face characteristics such as identity, gender, age, and ethnicity. These variables have attracted great interest due to the availability and affordability of equipment and software which have made this approach to research easier and more reliable.

IMPORTANT CONSIDERATIONS ABOUT METHODOLOGICAL PROCEDURES

Standard Recording Devices

Webcam and Computer with and Automated Facial Expression Analysis Software

Automatic Facial Expressions Analysis (AFEA) is one of the most popular technologies within human behavior research since it does not require any sensors being attached to the participant. Furthermore, facial expression algorithms allow for a more detailed insight into emotional processing as reflected by stimulus-driven or self-elicited emotional reactions such as joy, anger, fear, surprise, confusion, and so on. Combining facial expression analysis with physiological recorders that monitor arousal (e.g., pupil dilation, EEG, or EDA) allows the experimenter to not only monitor and determine which emotions are being expressed but go further and evaluate the intensity of the expressed emotions.

The experimenter will need a camera and appropriate software. Computer-based facial expression analysis mimics human coding skills by capturing raw, unfiltered emotional responses toward any type of emotionally engaging content (see figure 10.2).

Facial Electromyography (fEMG)

With fEMG, the experimenter can track the activity of facial muscles with electrodes attached to the participant's skin surface. fEMG detects and amplifies the tiny electrical impulses generated by the respective muscle fibers during contraction. The most common fEMG sites are in proximity to the

Figure 10.2 iMotions' Automated Facial Recognition Software. *Source*: Image courtesy of iMotions, Inc.

following two major muscle groups: (1) the right/left *corrugator supercilii*: this is a small, narrow, pyramidal muscle near the eye brow, generally associated with frowning. The *corrugator* draws the eyebrow downward and toward the face center, producing a vertical wrinkling of the forehead. This muscle group is active to prevent high sun glare or when expressing negative emotions such as suffering and (2) the right/left *zygomaticus* (major): this muscle extends from each cheekbone to the corners of the mouth and draws the angle of the mouth up and out, typically associated with smiling. The advantages of using fEMG include the fact that it is a noninvasive, precise, sensitive method to continuously measure facial muscle activity; it also does not depend upon language and does not require cognitive effort or memory; and it is able to measure even very subtle facial muscle activity even in scenarios where respondents are instructed to inhibit their emotional expression. However, the disadvantages of using fEMG may be being somewhat intrusive because it requires electrodes, cables, and amplifiers; for this reason, it might change participants' responses; it is sensitive to motion artifacts and electrical interference; its analysis requires expert biosensor processing skills.

Recommendations for Data Collection

Setting up the proper environment for data collection involves considering the proper camera, camera lens, camera settings, camera placement, participant positioning, proper illumination, and visibility of the participant's face. The researcher also needs to consider how to properly set up the experimental stimuli, taking into account measures to avoid activities or objects that might decrease the quality of the data collected.

Webcam

A webcam must be used along with a computer where the acquisition and analysis software has been installed.

Camera Lens

For facial expression analysis, the researcher will need a webcam with a standard lens; wide-angle or fisheye lenses should be avoided as they may distort the image and cause errors in processing.

Recording Resolution

The minimum recording resolution varies across facial expression analysis engines. An HD or 4K resolution camera is not needed because automated facial expression analysis works for low resolutions as long as the participant's face is clearly visible. However, the resolution of the video should be at least 640 x 480 pixel.

Recording Framerate

The camera should have a stable framerate of 10 fps or higher. However, it is possible to process video feeds with 60 fps or more. For offline coding, a framerate of 10 fps or higher is recommended.

Autofocus

It is highly encouraged to select a camera that is able to automatically track participants' faces within a certain range of distance. Some camera models offer additional, software-based tracking procedures to make sure that participants stay in focus.

Aperture, Brightness, and White Balance

Most cameras are able to automatically adjust to different lighting conditions. However, in case of backlighting, the gain control in many cameras reduces image contrast in the foreground, which may deteriorate performance. Therefore, it is preferable to place the participant in such way that the lighting source is in front of them, not behind.

Video Formats and Compatibility

The most commonly supported video formats are MP4, MOV, and WMV. However, some cameras generate videos in a variety of formats. If the video is rendered in a nonsupported format, it is possible to convert it to a more common format using a freely available video converter tool.

Camera Placement and Participant Positioning

The researcher should position the camera at the participant's eye level such that it faces the respondent directly. Face angles of about 20 degrees are acceptable, but automatic facial expression analysis delivers better results if the face is roughly centered in the frame. When presenting screen-based stimuli, attach the camera either above or below the screen. If participants are expected to use a keyboard, chances are they will look down frequently. In this case, the face detector will report missing data. To prevent this, the researcher can place the camera below the monitor, making sure that the participant's face is captured at the required minimum size. Participants should be seated comfortably to guarantee they will stay within the frame and in focus for the entire recording.

Illumination

Face tracking and facial expression analysis operate best with indoor, uniform, diffuse illumination. Adjust the setup to standard contrast. Use indirect ambient light as it illuminates the face evenly. Professional setups often use a softbox diffuser to create optimal lighting conditions.

Avoid dim lighting because facial expression analysis does not work in the dark. Avoid strong lights in the background (e.g., from a window or an artificial light source behind the participant's head). Also, strong directional lighting on one side of the head (e.g., direct sunlight with strong shadows) causes high contrast, potentially leading to issues in the facial expression analysis.

Visibility of Participant's Face

Facial expression analysis requires the visibility of emotionally sensitive facial landmarks such as eyebrows, eyes, nose, and mouth. Therefore, these areas must not be blocked or be kept out of frame from the camera; otherwise the face tracking and expression analysis may lead to only partial results. The researcher should ask participants to not wear sunglasses and overly large glasses that cover the eyebrows as they will interfere with proper face capture. Long beards that hide the mouth are not ideal, but short stubbles are okay. Facial jewelry, such as multiple mouth and eyebrow piercings can have a negative impact on the results. Participants should avoid wearing any kind of hats as they are likely to cast shadows and occlude facial landmarks. Hair styling that partially covers the face (e.g., long bangs covering the forehead) should be pulled back. Finally, the researcher should instruct participants to not occlude their faces with their hands or rest their heads on their hands.

Avoid Recording While Participant Is Talking, Eating, or Drinking

These activities involve movement of the lower facial muscles, particularly in the area around the mouth and cheeks. While these activities will most likely not have any impact on face tracking, they certainly cause changes in facial expressions. As participants talk, automatic expression coding procedures might incorrectly classify the muscular activations as indicator for the presence of certain emotions.

Neutral Baseline

In order to evaluate participants' facial expression characteristics, some facial expression analysis engines require the collection of a *neutral* face expression during a baseline period, which ideally is around 5 to 10 seconds long and placed at the beginning of the actual data collection. In this condition, no stimuli are presented. Respondents are just sitting in a comfortable, relaxed position and look "neutrally" toward the camera. The recorded data reflects the respondent's individual baseline expression in presence of neutral stimuli.

Baseline with Variable Stimuli

This condition contains stimuli with varying emotional content (e.g., a video with scenes that elicit neutral, positive, and negative emotions). The variable baseline is considered to max out a participant's facial expressions, comprising the full spectrum of neutral expressions and expressions with high positive and negative valence.

Setting Up the Experimental Stimuli

Once the baseline has been collected, the researcher is ready to start a recording in the desired test environment with the participants containing the stimulus set of interest. Facial expressions are very responsive and occur within tens to hundreds of milliseconds after stimulus onset. As a consequence, the researcher should present any material long enough for participants to process its content. This holds true for all sensory modalities: vision, hearing, taste, smell, and touch. In addition, it might be useful to place neutral stimuli of appropriate duration between the stimuli of interest in order to allow facial expressions to return to the neutral baseline state.

Access to Free and Standardized Visual Stimuli

The researcher can request access to the International Affective Picture System (IAPS), which is a database that has been specifically designed for emotion and attention research, comprising about 1,000 standardized color photographs that have been rated based on their emotional content. The IAPS is widely used in several fields of academic and commercial research.

Recommendations for Data Processing

The use of specific software that comes with the hardware that the researcher has selected will facilitate data output and visualization. Automatic facial expression analysis returns numeric scores for facial expressions, AUs, and emotions along with the degree of confidence. Most generally, the researcher can think of these metrics as detectors: As the facial expression or emotion occurs and/or intensifies, the confidence score rises from 0 (no expression) to 100 (expression fully present). The numerical values representing the facial expression can be plotted and visualized for both static images and videos (frame by frame time-course of emotion scores).

Facial Action Coding System

The FACS is a tool for classification of all facial expressions that humans can make. Each component of facial movement is called an AU and a basic premise is that all facial expressions can be broken down to action units[1] (see table 10.1).

FACS represents a fully standardized classification system of facial expressions for expert human coders based on anatomic features. Experts carefully examine face videos and describe any occurrence of facial expressions as combinations of elementary AUs. FACS is the measurement system, and it does not interpret the meaning of the expressions. It is later, during the analytical phase, that the FACS system allows for a modular construction of emotions based on the combination of AUs (see table 10.1). With facial AU coding, the experimenter can obtain information pertaining to facial macro-expressions, microexpressions, and other subtle expressions associated with the *intensity* and *depth* of the underlying emotion.

Advantages of Using FACS

There are several reasons to consider using the FACS as part of a study on emotional responses: (1) facial action coding is a nonintrusive, objective,

Table 10.1 Action Units and Descriptions. Examples of Action Units Used in the Facial Action Coding System along with a Description of What Kind of Facial Expression, Head Movement, Eye Movement, or Emotion They Refer To

AUs No.	*Description*
1	Inner Brow Raiser
2	Outer Brow Raiser
4	Brow Lowerer
5	Upper Lid Raiser
6	Cheek Raiser
7	Lid Tightener
8	Lips Toward Each Other
9	Nose Wrinkler
10	Upper Lip Raiser
11	Nasolabial Furrow Deepener
12	Lip Corner Puller
13	Cheek Puffer
14	Dimpler
15	Lip Corner Depressor
51	Head Turn Left
52	Head Turn Right
53	Head Up
54	Head Down
61	Eyes Turn Left
62	Eyes Turn Right
63	Eyes Up
64	Eyes Down
Happiness = 6 + 12	Cheek Raiser, Lip Corner Puller
Sadness = 1 + 4 + 15	Inner Brow Raiser, Brow Lowerer, Lip Corner Depressor
Surprise = 1 + 2 + 5 + 26	Inner Brow Raiser, Outer Brow Raiser, Upper Lid Raiser, Jaw Drop
Fear = 1 + 2 + 4 + 5 + 7 + 20 + 26	Inner Brow Raiser, Outer Brow Raiser, Brow Lowerer, Upper Lid Raiser, Lid Tightener, Lip Stretcher, Jaw Drop

Source: Table created by author.

systematic method to describe facial expressions; (2) emotional interpretations emerge only during the data processing stage; (3) its scores have a high face validity as they are based on visible changes in facial tissue; and (4) its scores also contain a five-step intensity rating.

Disadvantages of Using FACS

There are several disadvantages to consider before deciding to use this research methodology: (1) coding requires high-quality video equipment; (2) scoring relies on the trained discrimination of experts, rendering the coding very laborious and expensive. For example, a well-trained FACS coder can take up to 100 minutes to code 1 minute of video data depending on the density and complexity of facial actions; and (3) training itself is resource-intense, requiring studying the FACS manual extensively, followed by the completion of the FACS certification.

The FACS was updated in 2018—The *F-M Facial Action Coding System 3.0* (see F-M FACS 3.0)—and it now contains 4,000 videos and images in ultra-definition 4K, using 3D technology and automatic real-time recognition, using a software called *FaceReader 7.1*. The F-M FACS 3.0 features eight additional AUs and twenty-two additional tongue movements (TMs), as well as additional functional and structural nomenclature (Freitas-Magalhães, 2018).

Reliability of Ground Truth Coding

The labeling of employed databases not only determines whether a given system attempts to recognize or interpret facial expressions but may also influence the achievable recognition accuracy, especially when it comes to facial expression timing and intensity estimations. Furthermore, chosen classification schemes affect the design of facial expression classifiers, for example they have an influence on the number and nature of facial action categories that have to be treated. According to Ekman (1982), there are several points that need to be addressed when measuring facial expressions: (a) a separate agreement index about the scoring of specific facial actions, as typically some actions are easier to recognize than others, (b) spontaneous rather than posed facial actions, (c) various subjects including infants, children, adults, and aged populations, (d) limiting the disagreement in the judgment of facial actions by providing a minimal intensity threshold of facial actions, (e) inclusion of both expert and beginners for the measurement of facial actions, and (f) the reliability should be reported not only for the type but also the intensity and dynamics of facial actions. These points can probably be easier fulfilled with sign than with judgment-based approaches as the latter can only provide a limited labeling accuracy. For example, within a single basic emotion category, there is too much room for interpretation.

Furthermore, cross-cultural studies have shown that the judgment of facial expression is also culturally dependent and partially influenced by learned display rules (Matsumoto, 1993). Even though the aforementioned basic emotions are universal across cultures, the assessment is hampered, if the encoder and decoder are of different cultures (Matsumoto, 1990). Sign-based coding schemes on the other hand increase objectivity, as coders are only required to record specific concerted facial components instead of performing facial expression interpretation. An advantage of sign-based methods is also the possibility of decomposing facial expression recognition and facial expression interpretation. Hence, the performance of the employed analysis methods may be evaluated directly with regard to their visual performance.

Today, most facial expression analysis systems attempt to map facial expressions directly into basic emotional categories and are thus unable to handle facial actions caused by nonemotional mental and physiological activities. FACS may provide a solution to this dilemma, as it allows to classify facial actions prior to any interpretation attempts. So far, only marker-based systems are able to reliably code all FACS AUs activities and intensities.

NOTE

1. For more information on the complete FACS along with video snippets of each facial expression, refer to iMotions' *Visual Guidebook* (by Bryn Farnsworth, retrievable from https://imotions.com/blog/facial-action-coding-system/)

Conclusion

This book discussed how research methods in psychophysiology can be applied to the study of contextualized and socially oriented use of language with the help of multimodal discourse analysis. In the study of "authentic" language use in group conversations, discourse analysts have traditionally used video recording to register these events and transcription conventions to transfer such exchanges onto standardized text format. Such conventions have helped this community of practice to analyze and understand the organization under scrutiny in systematic ways. A multimodal discourse analysis representation of a video-recorded conversation enables the researcher to assign pragmatic meaning to words, phrases, and sentences uttered at turns during such conversations. Using psychophysiological methods to multimodal discourse analysis will the experimenter explore the data beyond the immediate pragmatic and semantic meaning of such verbal exchanges, allowing them to more confidently assign discourse intentionality beyond the obvious connotations and denotations in the evolving communicative event. Therefore, a discourse analyst that utilizes multimodality in their research and decides to make use of psychophysiology in their research may enlist research participants' bodily responses to the ongoing video-recorded interaction that go beyond the usual pairing of talk to facial expressions, hand gestures, body orientations, gaze, intonation, pitch, prominence, and other biosemiotic resources visually and aurally available to observers. Given that psychophysiological responses are resources that are also available to conversation participants—both speakers and hearers—and that they convey shared knowledge and experiences, they are as important as words (or signs) are, and their inclusion in studies of discourse and communication is imperative.

Throughout the field of applied linguistics, there has been an increase in interest in the usefulness of neurobiological measurements to further investigate language learning, language use, and language cognition. Language researchers outside of applied linguistics (e.g., neurolinguists, psycholinguists) have already attuned to the clues lodged in respiration patterns, heart rate variability, eye movement, pupil dilation, brain waves, among other physiological data. Recording participants' changes in autonomic responses can yield valuable qualitative information about their investment in the conversation. This is due to the fact that the brain's motor and autonomic systems are informed by and react to environmental cues available during the conversation, both from other participants and from the surrounding environment. Making use of psychophysiological methods in discourse analysis can yield valuable information about how such individual differences can shape social interaction.

The increasingly transdisciplinarity in scientific investigations today has allowed the transfer of methods from one discipline to another, allowing research to cross discipline boundaries while staying within the disciplinary framework. Christiansen and Chater (2017) argue that the study of language has fragmented into many highly specialized areas of study that tend not to talk to each other, and they suggest that language sciences should strive to understand the nature of language by taking an integrated approach. They claim that this is a "new era of integration" and that each discipline that aims at studying human language from the stand point of evolution, its processing, or production needs to stop looking at the pieces of this puzzle in isolation, thus ignoring the information potentially contained in other pieces. They posit that "the crossword of nature can only be solved by integration and relentless interaction across disciplines" (p. 2). Regardless of the research methods used to obtain data related to language processing, language use, and language acquisition, language production, whether the language was presented aurally, in written form, through imagery, or through haptics, and whether the study subjects were in isolation or in groups and performing social engagement behaviors, communication is the one variable they have in common, which means that several aspects of these datasets should intersect. However, the challenge of exploring how and where these methods intersect undoubtedly lies in the integration of several different kinds of data, requiring the well-informed choice and use of equipment, software, coding, data collection protocols and qualitative and/or quantitative data analysis, using a multimodal discourse analysis approach. All disciplines in the social sciences and humanities interconnect in their interest in human communication, and only by working together can language scientists solve this seemingly overwhelming puzzle.

This book has also shown that research using peripheral physiological sensors can provide information about emotional, cognitive, and attentional states during linguistic tasks that is more reliable than self-reports or that can corroborate self-reported information. Equipped with this knowledge, applied linguists can design research studies that make use of physiological recordings to better understand linguistic behaviors. For example, eye trackers have been used to assess the effect of interruptions on the performance of a person executing a task (Bailey et al., 2008); an eye-tracking device, EEG, ECG, and heat flow analysis were used to measure the mental workload of basic tasks such as the resolution of problems on a monitor, visual perception, and cognitive speed by using, and it was found that ECG and heat flow together identified between high- and low-task cognitive demand with 80% precision (Haapalainen et al., 2010); it has been shown that mental workload can be measured by pupil dilation (Xu et al., 2011); an eye-tracking device, a pressure sensor for the mouse, an EDA sensor, and a pulse oximeter (for measuring HR and level of oxygen in the blood) were used to measure mental load during tasks, and it was found that EDA and pupil dilation have the greatest statistical significance in terms of detecting task difficulty (Ikehara et al., 2005). In sum, there is a vast and fast-growing literature proving the efficiency of physiological methods in the research of underlying emotion regulation, cognitive processes, and linguistic performance, and these methods have enormous potential in advancing communication and language studies. Nevertheless, in order for that to be the case, attention to proper procedures is crucial in order for the data to be reliable, reproducible, and meaningful.

Appendix

Physiological Recording Instruments Not Included in This Book

FNIRS

Functional near-infrared spectroscopy (fNIRS) records the diffusion of near-infrared light by human skull, scalp, and brain tissue, allowing researchers to monitor cerebral blood flow in specified brain regions. While fNIRS is a relatively new technology, it has already proven to be a very promising tool in human behavior research due to its noninvasive, portable, and inexpensive character. fNIRS can, for example, be used to monitor cerebral blood flow in frontal cortex as an indicator of cognitive workload (prefrontal activity) or motivation (prefrontal asymmetry). In the upcoming months and years, the application bandwidth for fNIRS will further grow, allowing you to answer more research questions on human behavior and cognition.

Near infrared spectroscopy is an optical technique for measuring blood oxygenation in the brain. It works by shining light in the near infrared part of the spectrum (700–900nm) through the skull and detecting how much the remerging light is attenuated. The amount of the light attenuated depends on blood oxygenation, and thus NIRS can provide an indirect measure of brain activity.

MEG

Magnetoencephalography (MEG) is an imaging technique used to measure the magnetic fields produced by electrical activity in the brain via extremely sensitive devices known as SQUIDs. These measurements are commonly used in both research and clinical settings. There are many uses for the MEG, including assisting surgeons in localizing a pathology and assisting researchers in determining the function of various parts of the brain, neurofeedback, and others.

PET

Positron emission tomography (PET) uses trace amounts of short-lived radioactive material to map functional processes in the brain. When the material undergoes radioactive decay a positron is emitted, which can be picked up by the detector. Areas of high radioactivity are associated with brain activity.

CT

Computed tomography (CT) scanning builds up a picture of the brain based on the differential absorption of X-rays. During a CT scan the subject lies on a table that slides in and out of a hollow, cylindrical apparatus. An X-ray source rides on a ring around the inside of the tube, with its beam aimed at the subject's head. After passing through the head, the beam is sampled by one of the many detectors that line the machine's circumference. Images made using X-rays depend on the absorption of the beam by the tissue it passes through. For example, bone and hard tissue absorb X-rays well, whereas air and water absorb very little X-rays, leaving soft tissue somewhere in between. Thus, CT scans reveal the gross features of the brain but do not resolve its structure well.

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Bahiyyih Hardacre is an assistant professor in Applied and Advanced Studies in Education, a division of the Charter College of Education at California State University Los Angeles. Her research interests include the role of neurobiology in language learning, language production, language assessment, and language pedagogy. She is particularly interested in the role of the autonomic nervous system in social engagement behaviors during face-to-face interactions in first- and second-language production. She makes use of psychophysiological data in multimodal discourse analysis in order to study language use during communicative events.