UNIVERSITY OF PADUA

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Final report

Development of an EEG paradigm with rhythmic syllable-by-syllable presentation of sentence sequences

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Abstract

The phenomenon of brainwave entrainment means the brain, by analyzing the rhythm, responds to stimuli with frequencies matching the pattern presented. In this thesis I deal with entrainment and linguistic structures, specifically syllables, phrases and sentences, aiming to investigate whether the brain works with a hierarchical processing. The paradigm is an adaptation of the studies of Ding et al. (2016) and Ding, Melloni, Yang, et al. (2017) using Italian language, which requires a more complex experimental design: the stimuli are presented syllable-by-syllable with a standard rhythm and the EEG records the brain response. Entrainment to words in sentences have been originally interpreted as a sign of structural operations, however Frank and Christiansen (2018) showed with a computational model that the data can also be explained in terms of entrainment to lexical properties of single words. In our paradigm we profit of the word order flexibility of Italian language to try to disentangle the two explanations.

Contents

Chapter 1

A starting point: the literature behind the project

The elaboration of language in human's brain is still a mystery but nowadays many possible theories have been developed. There is currently a debate between two main theories, that is a hierarchical elaboration versus a sequential elaboration of language.
A hierarchical elaboration means that the person reads or listens to a language and the brain is able to break down that sentence or speech to the smallest unit, which usually is a syllable. Then the brain reassembles it creating words, phrases and sentences to understand the meaning behind by using internal grammatical principles that are the same governing language generation. So it is defined as "hierarchical" because of its pyramidal structure (Ding, Melloni, Tian, & Poeppel, 2017).
On the other hand a sequential elaboration means that the brain analyzes the language syllable-by-syllable without creating any bigger structure and it is able to understand the meaning behind only by referring to statistical information. It is also referred to as Chunk-and-Pass processing (Christiansen & Chater, 2016).
In this chapter I firstly introduce two studies that investigate the hierarchical elaboration of language, that is Ding et al. (2016) and Ding, Melloni, Yang, et al. (2017) and then a critique to the interpretation of their results by Frank and Christiansen (2018). Lastly I will briefly present the first paradigm that aims to reproduce the other studies but adapted to Italian language proposed by Yassin (2021). This introductive chapter is functional to understand the new paradigm with Italian language, presented in Chapter 2.

1.1 Ding et al. (2016): a first study with MEG and ECoG

The paradigm of the first study of Ding et al. (2016) is with Chinese and English language and the techniques used to record the brain responses are magnetoencephalography (MEG) for cortical tracking of phrasal and sentential structures and electrocorticography (ECoG) for neural source localization.

Since Chinese and English languages have a word structure more simple than Italian language the researchers decided to use four and eight syllables sentences and they analyzed the responses for different duration sentences but also for different syntactic structures. Specifically for the sequences of four-syllable sentences, there are monosyllabic words that can be independent (a,e) or create two phrases of two words that can be independent (b) or related (d,f), or again create a "1+3" structure (c). A stylized model for each linguistic structure is shown in Figure 1.1, as well as the cortical response spectra. The analyzed results suggest the validity of the hierarchical processing theory. As the linguistic structure becomes larger the spectral peaks get bigger also for the sentential and phrasal response.

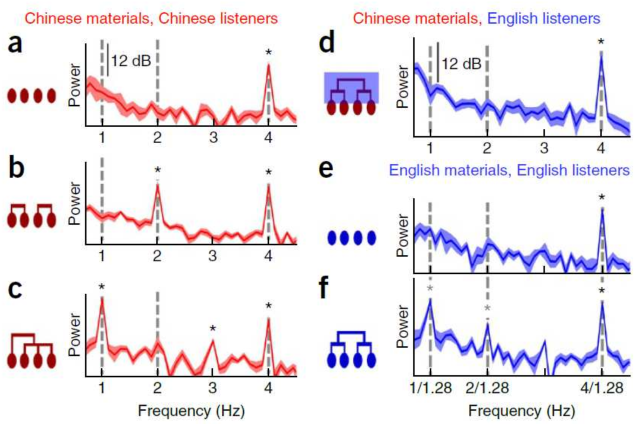

Figure 1.1: Tracking of different linguistic structures. Adapted from Ding et al. (2016).

The control condition is a random intertrial condition: this means that the syllables in the sentences are mixed between all the trials maintaining the same position they had in the original trial. For example in a four sentence syllable the first syllable in the sentence is replaced by the first syllable of a randomly chosen sentence.

1.2 Ding et al. (2017): an adaptation of the paradigm with EEG

Ding, Melloni, Yang, et al. (2017) investigated the hierarchical theory using electroencephalography (EEG) with 128 channels, a technique which is way more available than MEG and ECoG. The stimuli and procedures are the same of one of the conditions contained in the MEG study: the sentences are four syllables long and in English. The participants were all young adult native speakers without any language disorders. The results analysis confirms the results obtained in the study of 2016: "the response to sentences shows three clear peaks at the sentential, phrasal and syllabic rates" while "For the control condition, only one peak at the syllabic rate is observed".

Furthermore the phrasal-rate response was more difficult to detect in individual subjects compared to the syllabic and sentential rate. This may be due to the fact that " The syllables have very clear acoustic boundaries and therefore can drive strong auditory responses. (...) the sentences also have relatively clear perceptual boundaries. The phrases within a sentence, however, are related both syntactically and semantically, which makes the boundaries between them less obvious than those between syllables and sentences. "

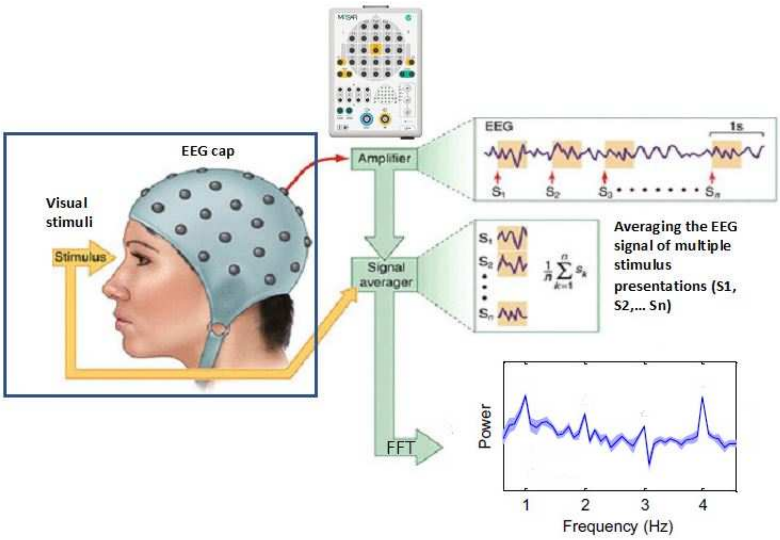

Figure 1.2: EEG structure and signal analysis. Adapted from Purves et al. (2008).

In Figure 1.2 is represented a simplification of the steps occurring during EEG recording and the signal analysis: the participant receives the visual stimuli; the electrodes in the EEG cap record the brain responses; the signal is then amplified by the amplifier and it is now ready for the filtering and averaging process. Then the Fast Fourier Transform (FFT) is applied to obtain the frequency spectrum of the signal. The signal contained in the spectrum is finally analyzed and interpreted.

1.3 Frank et al. (2018): a critique to the interpretation of the spikes

Frank and Christiansen (2018) is an article written as a response to Ding, Melloni, Tian, and Poeppel (2017). The authors want to clarify their point of view as an opposite to the rule-based hierarchical processing, already introduced in Frank et al. (2012). They think that language might be the product of sequential and statistical word-level processing. Furthermore they demonstrated how the MEG power spectra data showed in Ding et al. (2016) as evidence for hierarchical linguistic structure, can also be generated by a computational model trained with a feed-forward neural network (see Figure 1.3). The only linguistic information available to the model resides at the lexical level. "Hence, if power spectra predicted by the model are qualitatively similar to those from Ding et al.'s (2016) MEG experiment, these results can be explained from the stimulus' lexical properties alone and may therefore not indicate syntactic processes after all." (Frank & Christiansen, 2018).

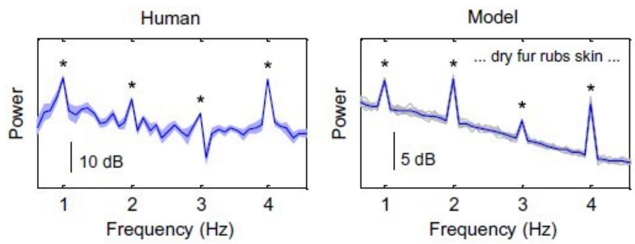

Figure 1.3: Power spectrum for English four-word sentences from Ding et al. (left; with adapted frequency scale) and corresponding model predictions (right). The shaded area (left) is the standard error over participants; and grey lines (right) are results from individual simulated participants. Blue lines represent averages over (simulated) participants. Adapted from Frank and Yang (2018).

1.4 Safa Yassin's thesis: a first design with Italian language

Safa Yassin (2021) wrote her bachelor's thesis proposing a paradigm of the experiment with Italian language. The aim is to reproduce the study and hopefully the results too of Ding, Melloni, Yang, et al. (2017) but to adapt it to Italian language some changes were necessary. The technique, EEG, is mantained but the stimuli presentation is visual instead of auditory. There are two conditions: the "copular" and the " mixed" and then there is the control condition. A sentence is composed of six syllables and a phrase is composed of three syllables: this means that each sentence contains two phrases. In this paradigm there are 30 trials, where 22 are "normal" and the other 8 are "outliers". Each trial contains 12 sentences, so in total there are 360 sentences. The task for the participants is to detect the "outlier" trials by clicking a button at the end of each trial.

Starting from her paradigm and having considered some limits, we decided to design a new paradigm by refining it before performing the experiment. More information on the conditions and the modifications applied are contained in Chapter 2.

This first paradigm with Italian language acts as a bridge between the studies on hierarchical language (Ding et al., 2016); (Ding, Melloni, Yang, et al., 2017) and their critique (Frank & Christiansen, 2018) and the new paradigm, which has the same goal, that is support the theory of a hierarchical elaboration of language and clarify how the critique on the interpretation of spikes can be refuted.

Chapter 2

The new paradigm: method

The new paradigm is designed as a sequel to the studies of Ding et al. (2016) and Ding, Melloni, Yang, et al. (2017) and an improvement of the one proposed by Yassin (2021). The main difference from the other studies is the language involved: the aim of the research is the same but we want to reproduce the results with Italian language instead of English or Chinese to support the theory and at the same time to enhance its generalizability to other languages.

2.1 EEG and stimulus presentation

We decided to use electroencephalography (EEG) as in Ding, Melloni, Yang, et al. (2017) but instead of an acoustic stimulus presentation we present them visually. This means that every syllable is presented at the centre of the screen in capital letters, with the same font, color and contrast but most importantly with the same duration. The established duration for each stimulus presented is 250ms, including a blank that prevents the overlapping of two identical syllables. Now let's dive deeper into the structure of the study and its conditions.

2.2 Conditions of the study

The paradigm has three conditions that we named "copular", " mixed" and the control condition. This means that compared to the studies introduced earlier the amount of conditions is reduced: this allows to have more trials of the same condition, that is more variability inside each condition.

2.2.1 “ copular ” condition

The first condition is “copular” which is structured as “subject + “è” + object”. At a syllabic level the subject is composed of three syllables and the object of two. In this way the sentence is formed by two phrases, each one of three syllables. The subject can be an article (*il,lo,la,i,gli,le*) plus a noun, for example “il cane” (= the dog) or in other cases is a proper name such as “Antonio”. The “è + object” is what makes it a “copular” condition: “è” means “is” and the object can be an adjective or an adverb, for example “bello” (= beautiful) or “alto” (= high).
To sum up complete examples of the copular condition are the following:

(1) Il$_{ART}$ cane$_{NOM}$ è$_{V.COP}$ bello$_{ADJ}$
The dog is beautiful

(2) Antonio$_{NOM}$ è$_{V.COP}$ alto$_{ADJ}$
Anthony is tall

In total there are 120 sentences that are distributed in 10 trials, so that each trial has 12 sentences.

2.2.2 “ mixed ” condition

The mixed condition is also composed by sentences that are six syllables long and phrases that are three syllables long but the internal structure is different. There are 30 different types of sentences, specifically classified, where some “copular” sentences are also included. The aim of this condition is to obtain the maximum variation of lexical factors, while maintaining the same sentence structure. The 30 types were mixed and balanced between trials so that there are 10 trials and each trial has 12 sentences that are a different type from each other.
CLASSIFICATION
The six-syllables sentences are classified according to many factors: lexical morphemes, functional morphemes, word onset, word offset and proper name.

This means we analyzed each syllable by these factors and we created a table in an Excel file with examples of sentences that represent each of the 30 types.
Here is an example of a sentence of the first type: *"Lo rompe di nuovo"*; see Figure 2.1 .

orto	posizione	struttura	Morfemi lessicali	Morfemi funzionali	word ONset	word OFFset	nome proprio	tipo
LO	1	mista	0	1	1	1	0	1
ROM	2	mista	1	0	1	0	0	1
PE	3	mista	1	1	0	1	0	1
DI	4	mista	0	1	1	1	0	1
NUO	5	mista	1	0	1	0	0	1
VO	6	mista	1	1	0	1	0	1

Figure 2.1: Mixed condition: type 1, sentence example.

The "0" corresponds to the absence of the factor and the "1" corresponds to the presence of it. "orto" is the sentence split in syllables; "posizione" represent the position of each syllable in the sentence; "struttura" is the condition of the sentence and "tipo" is the type of the sentence. In this case the condition is "mista", which means mixed condition, and the type is "1".
After finding thirty types of different sentences, we created twelve sentences for each type, including four "copular" sentences that have the same structure as the type they are included in, and we mixed and balanced them creating the ten groups. We used Excel files and manually balanced them.

2.2.3 control condition

The control condition has the function of avoiding any interpretation errors of the results of the other conditions. In this experiment we did an intratrial randomization: we took each syllable of a trial and mixed them between the twelve sentences of the same trial.
At first we manually analyzed each trial to avoid the creation of words but the task for the participants seemed too difficult so in the new control condition there is a single word in each trial, created by using the syllables already present in the trial. Further explanation of the task is contained in paragraph 3.1 . In Figure 2.2 there is an example of a sentence for each of the conditions, split in syllables. This representation enhances the fact that all syllables in the conditions are two or three letters long and this allows to maintain

a rhythmic visual presentation of the syllables without any interference which could be caused by longer syllables.

Copular → LA – NOT – TE – È – BU – IA

Mixed → STA – SE – RA – SUO – NIA – MO

Control → TER – DI – LEC – TAC – NIA – I

Figure 2.2: The three conditions: sentences examples.

2.3 Structure: lists of participants and layout of the experiment

The experiment is composed of four lists of participants arbitrarily called “A”,“B”, “C” and “D”. To create them it was written a code in R. “R is a free software environment for statistical computing and graphics.”(R Core Team, 2024) The code reads all the “.csv” files previously created for all three conditions and randomly distributes the trials in the four lists. The code in “.R” format is available on a repository on GitHub. (see paragraph 3.5 for more information). To the participants of all lists a practice trial for all the conditions is firstly presented to allow the participants to become familiar with the setting of the experiment and be more focused and precise during the real experiment. Then each list starts with a specific trial: list A with a mixed; list B with a copular; list C with a control (of a copular trial) and list D with a copular again. Regarding the following trials there is no constraint, so all the remaining trials are mixed between the lists.
Firstly the layout of the experiment was created in OpenSesame, which is a “ graphical experiment builder for the social sciences. OpenSesame is free, open-source, and cross-platform. It features a comprehensive and intuitive graphical user interface and supports Python scripting for complex tasks. Additional functionality, such as support for eye-trackers, input devices, and video playback, is available through plug-ins. OpenSesame can be used in combination with existing software for creating experiments.”(Mathôt et al., 2012).

Here is an example of the layout of OpenSesame:

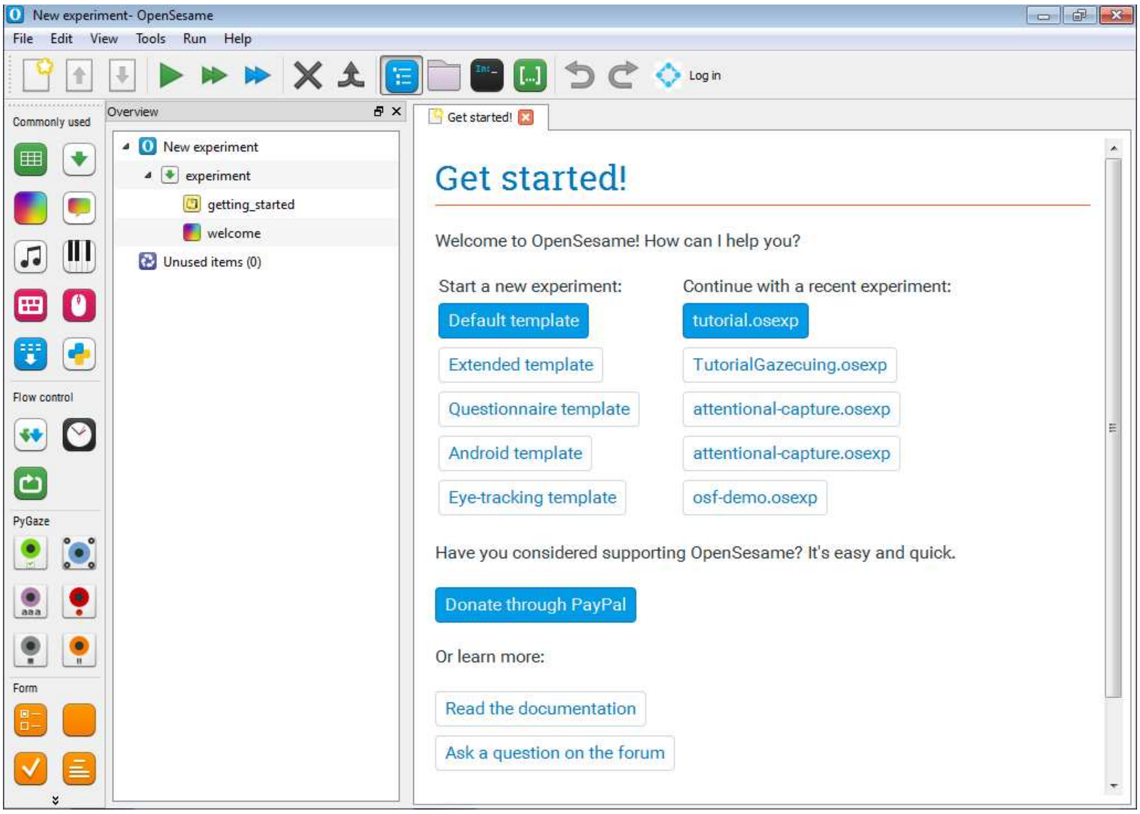

Figure 2.3: The OpenSesame user interface. Adapted from OpenSesame Documentation Team (2024).

Subsequently, the code has been tested in laboratory by checking the timing of the presentation inspecting the intervals between the presentation of the syllables both using the log of the program and the distance between markers recorded by the EEG system. Since the intervals showed large variations (above 5 ms) the program has been rewritten in Psychopy, using directly Python code instead of the GUI, allowing to create a simpler and more efficient code. "Psychopy is an open-source platform used to create experiments in psychology, neuroscience, and behavioral sciences. It allows users to design complex experiments through a graphical interface or by scripting in Python, supporting a wide range of stimuli and data collection devices."(Peirce, 2007).
Here is an example of the layout of Psychopy:

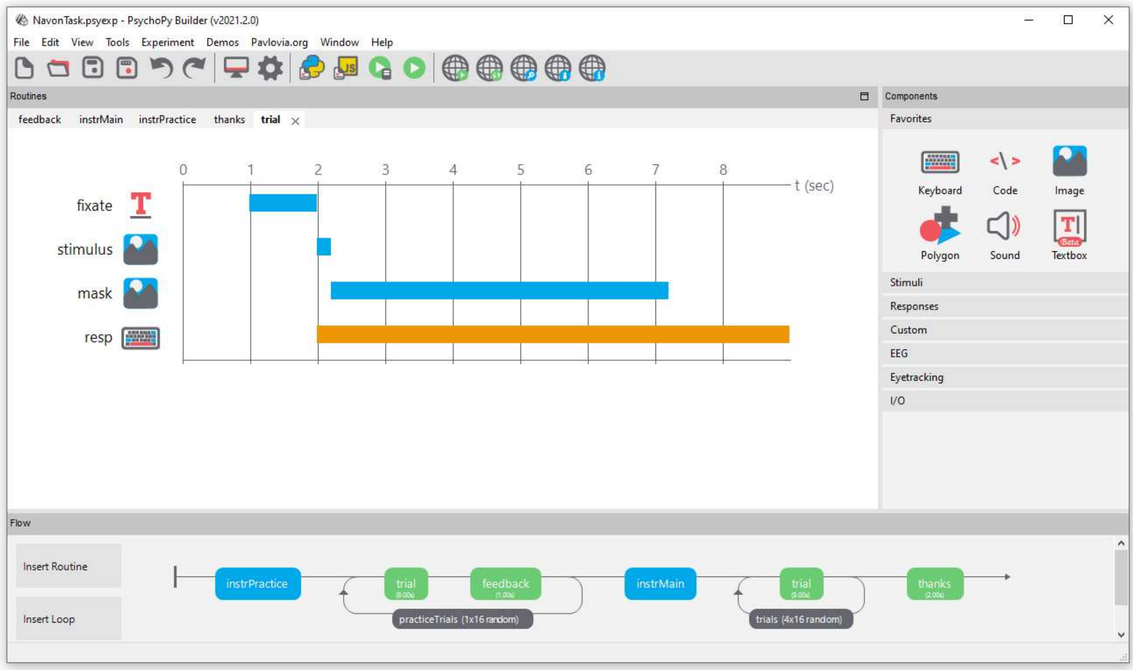

Figure 2.4: The PsychoPy Builder interface. The right-hand panel contains the Components that can be added to the experiment, organized by categories that can be expanded or collapsed. These Components can be added into Routines and appear like "tracks" in the Routine panel. Any number of Components can be set to start and stop in a synchronous or asynchronous fashion. The bottom panel of the interface shows the Flow of the experiment: the sequence in which the Routines will be presented, including the occurrence of any Loops in which we can repeat trials and/or blocks and control the randomization of conditions. Users report that this view is a highly intuitive and flexible way to implement their experimental designs. Adapted from Peirce et al. (2019) and PsychoPy Developers (2024).

Chapter 3

Future prospects

This final chapter is about the next steps that need to be done towards the realization of the experiment; a brief explanation of the possible results and their influence on other future studies; a sum up of the limits and advantages of this paradigm and finally the importance of giving access and being transparent during the whole process of the research.

3.1 The pilot and the task

After creating the design of the paradigm it is necessary to do a pilot before selecting the participants for the real experiment. The pilot is very useful and it means testing if the paradigm works as it is expected or if there are any errors in the program for example. A feedback from the participants is often a key aspect in understanding if the task requested is clear, neither too easy nor too difficult and if the aim of the experiment is also easy to understand. The pilot can sometimes enhance advantages or limits that will be evident during the real experiment. This means that the researchers while designing the experiment should develop the capacity to change their perspective to an external point of view, so that it is possible to predict or notice during the pilot specifically the limits of the design. This kind of work allows to do some adjustment to the final experiment and have a more clean design. Regarding the task we decided that the participant, at the end of each trial, should click a button to say if he/she has already seen a set of two or three syllables in that specific trial. We firstly manually selected the syllables in each trial so that they did not create any word to have an equal task between the conditions. After, we considered that this type of task may be too difficult, specifically for the control condition that doesn't contain any real word (see paragraph 2.2.3). To make the new task easier, a real word was added to each trial of the control condition, using the syllables already existing in it. For the other two conditions (copular and mixed), the syllables selected for the task were simply switched with a real word that may or may not be in the trial. The task for the participant is the same: detecting a sequence of syllables (that now forms a real word) and clicking a button to say if the sequence is or is not present in the trial. In this experiment there is the same task for all the participants in all the conditions. This may seem restrictive in some way but Ding et al. (2016) already tested many conditions with different tasks revealing that it is quite irrelevant the difference between them. Moreover we already adapted the paradigm to a different language and applied some adjustments so I think it is a good idea to have a clear and repetitive task for all conditions. This modus operandi leads to a more understandable design of the experiment and hopefully more clear results to analyze and interpret.

3.2 Selection of participants

When the pilot and the little adjustments have been carried out, it is time to start the selection of participants. There is usually a list of requirements but the strictness of them depends on the nature of the experiment. In this case the requirements will be for example the knowledge of Italian language and no severe visual impairments that would of course interfere with the performance of the participants. Before starting the selection it is important to choose how many participants are needed and balance characteristics such as gender and age. When the participants have been selected it is now time to arrange when to carry out the experiment taking into account their availability. Having completed this steps everything is ready to start the experiment.

3.3 Analysis of the results: Ding VS Frank?

During the experiment the signals of each participants are recorded individually. It is necessary to apply some filters to remove any artifacts that can be due to external factors or to something related to the participant: blink, cough, sweat and all the movements that could create noise in the recorded signal. After this "cleaning" process it is necessary to combine the signal and average them so that it is possible to collect the redundant part of the signals that may be significant. The Fast Fourier Transform (FFT) is applied o obtain the frequency spectrum of the signal that can now be analyzed and interpreted. (see also Figure 1.2).

The difference between copular and mixed condition can disentangle between the two explanations of the phrase and sentence peaks found in Ding et al. (2016) and Ding, Melloni, Yang, et al. (2017). In fact both copular and mixed conditions have the same hierarchical structure (3+3) and thus, if peaks represent mental operations related to the building of hierarchical structures, these should be found in both conditions, that is similar in amplitude. On the other hand, if peaks respond to rhythmic presentation of lexical properties of the signal (as proposed by Frank and Christiansen, 2018) only the copular condition should show clear peaks since in the stimulation there is a clear rhythm of grammatical categories (nouns, copula, adjective) and of root vs functional morphemes while the mixed condition has a number of different structures which minimizes the rhythmicity of lexical and sub-lexical properties.

3.4 Advantages and limits of the paradigm

As already mentioned in Chapter 2, this paradigm aims to reproduce and at the same time expand Ding et al. (2016, 2017) studies. At this point only English and Chinese languages have been tested so if the results match, the use of Italian language allows to generalize Ding's theory to another language. Other research groups could start from this paradigm and adapt it to their language too to add validity to the results on a cross-linguistic level. Furthermore Italian language has very rhythmic syllables, which is similar to Chinese characters, but also a complex grammar: that allows to test the theory with many different structures. These results are crucial to understand if Frank and Christiansen (2018) critique can be applied to various grammar structures.

The choice of visual stimuli presentation implies to take into account the speed of reading and requires no visual impairments while with the acoustic stimuli presentation it would

have been necessary to synthesise each syllable. In future studies it may be a good option to use both visual and acoustic presentation simultaneously. Using two techniques together can allow to record a stronger EEG signal or it may be that one technique interferes with the other and we have an even more noisy signal.
Regarding the task, it is always very important to test it with a pilot before the real experiment. A task which is not clearly explained or a task that engages the participant too much or too little may influence a lot the brain responses, that is the EEG recordings and the overall study. Since this is the first time this paradigm is applied it is important to make sure that the participants have well understood what the experiment is about and that the task is very clear. To facilitate this process a practice for each condition is submitted to the participant before the real experiment (see 2.3). After this, the participant has still time to ask more question before the starting of the experiment.

3.5 An Open Science project

Research in the field of psychology is currently going through a critical phase. Specifically the self-correction process, which should happen for every scientific discipline to guarantee the veracity of the literature, is not as effective as we think. (Klein et al., 2018) This situation happens when the researchers do not give access to the key products such as materials, data, analyses and protocols. In this way the scientific community cannot examine the process behind the results and the conclusions presented and the researcher is tempted by the possibility of selecting only the results that fit with the narrative of its own research. Nowadays many tools and services that promote Open Science are available and various scientific journals are adopting the Transparency and Openness Promotion guidelines (TOP) (Nosek et al., 2015) to encourage transparent research practices. In their paper Klein et al. (2018) present a practical guide, easy to understand, with all the aspects to consider for conducting a transparent research such as what, when and how to share: *"Our view is that being an open scientist means adopting a few straightforward research management practices, which lead to less error-prone, reproducible research workflows with each incremental step adding positive value."*. Since we deeply agree with the importance of transparency in the field of research, we chose to share all the files and the Python code created for this specific paradigm in a repository on GitHub. GitHub is a cloud-based platform where you can store, share, and work together to write code. Storing your code in a ”repository” on GitHub allows you to: showcase or share your work; track and manage changes to your code over time; let others review your code, and make suggestions to improve it. (GitHub Docs, 2024). Here is the link to access all the material and information on the paradigm and the future study: *https://github.com/caligiu/entrainment_eeg*.

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