UNIVERSITÀ DEGLI STUDI DI PADOVA

Dipartimento di Psicologia Generale

Corso di Laurea in Neuroscienze e Riabilitazione Neuropsicologica

Tesi di laurea magistrale

EXPLORING CEREBRAL AND PUPILLOMETRIC MARKERS OF SUGGESTIBILITY IN HEALTHY ELDERLY INDIVIDUALS: FORENSIC IMPLICATIONS

Exploring cerebral and pupillometric markers of suggestibility in healthy elderly individuals: forensic implications

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Anno accademico: 2024/2025

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INTRODUCTION

Suggestibility is considered a multidimensional construct that has been highly studied in different fields of psychology. Particularly, *Interrogative Suggestibility* has been the focus in the most recent forensic studies, especially since the development of the Gudjonsson Suggestibility Scale (GSS).

In legal context, this is particularly crucial when determining the validity of an eyewitness testimony or a self-incriminatory confession: the stressful situation coupled with a high suggestibility trait would be detrimental to its validity. This is especially true for vulnerable individuals, such as elderly population, in which suggestibility could be amplified due to declining cognitive functioning of natural aging.

Given the crucial role that this trait displays, are there any other methods that would measure suggestibility and enhance the assessment of testimonial validity?

The present thesis aims to *investigate* two potential physiological markers: cerebral and pupillometric measures. Specifically, by referring to the cognitive load framework, brain rhythms and pupil size were analyzed during a resting state condition.

Thus, the use of the electroencephalography, an established technique in neuroscience, combined with the eye-tracker, a particularly suitable approach due to its ease of application, represents an innovative approach to contribute to the assessment of testimonial validity in the forensic context.

CHAPTER 1: INTERROGATIVE SUGGESTIBILITY (IS) IN HEALTHY ELDERLY INDIVIDUALS

1.1. Interrogative Suggestibility (IS): theoretical approaches

Suggestibility is considered a transversal and multifaceted construct: many studies have been conducted to properly classify its sub-components.

For example, the pioneering work of Eysenck & Furneaux (1945) centers on the main subdivision of Suggestibility in *Primary suggestibility* and *Secondary suggestibility*.

The primary type refers to 'ideo-motor tests', involuntary movements triggered by the experimenter's repetitive and monotonous suggestions. Closely associated within a psychodynamic approach, it is highly correlated within hypnotizability (Gudjonsson, 2003).

The secondary type refers to a broad range of phenomena, associated with sensory processes and perceptual judgements (Gudjonsson, 2003). Its complex and elusive nature has led to several theories that intended to elucidate associated phenomena (Binet, 1900; Stukát, 1958; Sherif, 1936; Coffin, 1941; Asch, 1942).

Gudjonsson (2003) identified another type of suggestibility, that has little resemblance to the original subdivision conceived by Eysenck & Furneaux: *Interrogative suggestibility*.

Interrogative suggestibility (IS) is a form of suggestibility that derives from how individuals respond under interrogation conditions (Gudjonsson & Clark, 1986). The construct of IS is primarily implemented in the legal and forensic context, particularly in eyewitnesses' testimony.

It is possible to identify two different, yet complementary, approaches towards interrogative suggestibility: the *Individual differences approach* (Gudjonsson, 2003) and the *Experimental approach* (Schooler & Loftus, 1986). The specifics of each approach will be displayed in the next paragraphs.

1.1.1. Gudjonsson & Clark: the *Individual differences approach*

In the *Individual differences* approach, Gudjonsson (2003) define Interrogative suggestibility (IS) as "the extent to which, within a closed social interaction, people come to accept messages communicated during formal questioning, as a result of which their subsequent behavioral response is affected” (Gudjonsson, 2003, p. 345).

Gudjonsson & Clark (1986) defined Interrogative suggestibility in five main points:

1. A form of social interaction;
2. An interrogatory procedure;
3. A type of suggestive questioning;
4. An acceptance of the suggestion;
5. A behavioural answer.

Particularly, according to their theoretical model, “suggestibility refers to the tendency of the individual to respond in a particular way to suggestions. Therefore, whereas suggestion refers to the properties contained in a stimulus, suggestibility refers to the characteristics of the person who is being incited to respond” (Gudjonsson, 2003, p. 336). The model has specific domains of applicability to police interrogation. Moreover, it views suggestibility as being dependent upon the coping strategies people can generate and implement when confronted with the uncertainty and expectations of the interrogative situation (Gudjonsson, 2003).

This model of Interrogative suggestibility consists of two main aspects of suggestibility: the *leading questions* and the *negative feedback* (Ridley et al., 2013).

Leading questions refer to earlier works of Binet (1900). Specifically, Gudjonsson & Clark emphasized the impact that questions have on the accuracy of a witness’s report, by giving misleading prompts.

Furthermore, Gudjonsson & Clark identified three essential prerequisites that are required in the processing of questions (Gudjonsson et al., 2016):

1. *Uncertainty*: when the individual does not know for certainty the answer, take a significant part of the premise in the response;
2. *Interpersonal trust*: the idea that the examiner intentions are genuine;
3. *Expectation of success*: reluctance to declare the lack of knowledge from the tendency of individuals to feel compelled to know the answer.

These three components are essential in the process of suggestibility and are closely linked to the coping strategies the interviewee employs. The cognitive appraisal, subsequently, results in either a *suggestible* or *behavioural* response (Figure 1).

The *negative feedback* relates to the witness's tendency to modify its own answers subsequently the received feedback. It's closely related to uncertainty: greater levels of suggestibility derived from the interrogator's negative feedback that induces uncertainty in the interviewee. The negative feedback does not need to be stated explicitly. Even repeating the same questions can be considered an implicit form of negative feedback.

In conclusion, the model proposed by Gudjonsson & Clark (1986) focuses on the relative stable characteristics of the individual that mediate suggestibility (e.g. cognitive factors as memory and intelligence and personality factors as self-esteem, mechanisms of coping and anxiety proneness. Gudjonsson, 2003). (See further paragraph 1.2.1. Social, individual and cognitive factors associated with suggestibility).

Hence, although they continue to consider interrogative suggestibility as a *situation bound* dynamic process (Gudjonsson, 2003), the model proposes that individual differences can predict how the individual could react and cope under interrogative circumstances.

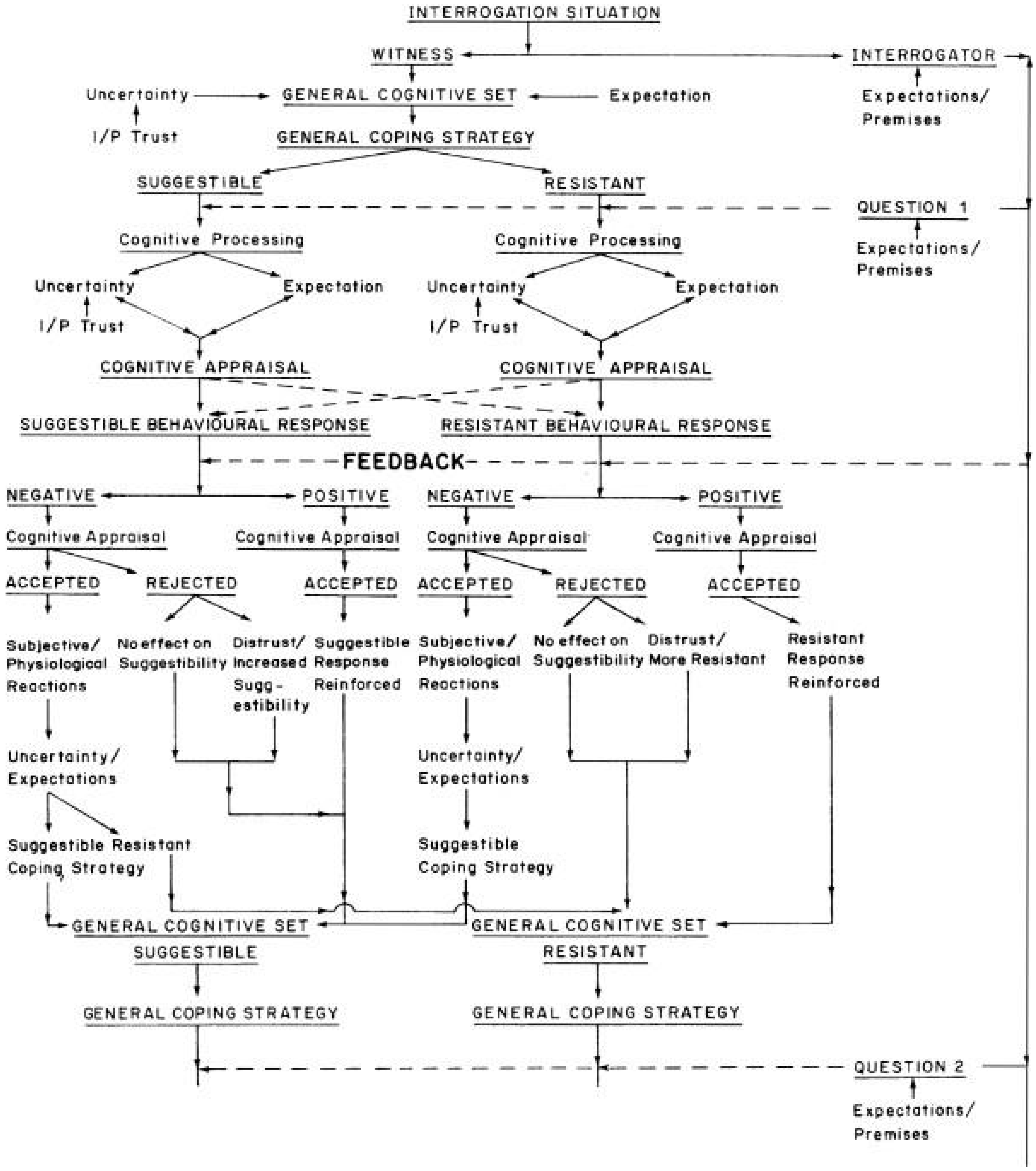


Figure 1. *A revisited theoretical model of interrogative suggestibility. (Gudjonsson & Clark, 1986)*

1.1.1.2. A scale to assess suggestibility: The Gudjonsson Suggestibility Scale (GSS-2)

Gudjonsson & Clark (1989) established a psychometric instrument to assess the suggestibility in the individual: the Gudjonsson Suggestibility Scale. Specifically, this scale permits to assess a person’s tendency to yield to leading questions and the degree of compliance with the interviewer's negative feedback. The authors created two parallel forms that differ on the content of the story: the GSS-1 (1984) is a crime-related story, whereas the GSS-2 (1986) has a more neutral narrative.

In this dissertation we will focus on the Italian version of the GSS-2 (Bianco & Curci, 2015), since it’s primarily used for the elderly population and in studies that focus on this age group (Dukala & Polczyk, 2014; Biondi et al., 2020).

The GSS-2 is a reliable and valid scale that satisfies the following criteria:

- It is an objective measure of how much the individuals yields;
- It is a measure of interrogative pressure;
- It permits an easy and speedy subministration;
- It is a reliable measure due to the sufficiently ample number of suggestive questions;
- It is a valid scale to measure suggestibility, resulting from the non manifest aim of the scale.

The procedure of administration of the GSS-2 is described in the following part: the examiner reads a story. At the end of the short story, the examiner asks the participant to say anything the person remembers. After 50 minutes of retention in which the subject is demanded to do non-confounding tasks, the participant is required to say everything he remembers from the story. Subsequently, the examiner poses 15 questions about the story: 10 of them are suggestive questions (therefore, the answer requires information that the subject cannot have), while the remaining 5 are non suggestive. Ultimately, the examiner gives a negative feedback, in a clear and explicit manner, containing the fact that the subject has done a certain number of errors. Therefore, the interviewer needs to repeat the same questions and asks the subject to be more accurate.

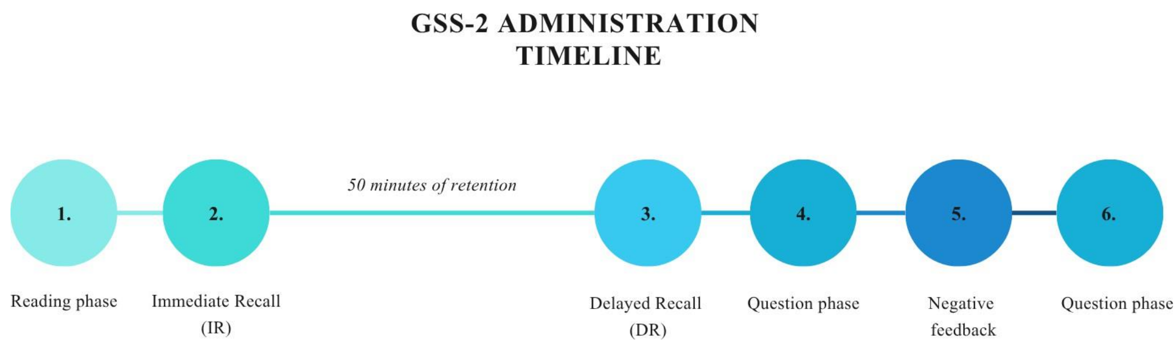


Figure 2. *Timeline of administration phases of Gudjonsson Suggestibility Scale (GSS-2).*

The questions administered can be categorized in three different types, each with a different grade of suggestibility:

- *Misleading questions*: they include salient premises that lead to answer in a certain way;
- *Affirmative questions*: they do not have a salient premise, but they can insinuate doubts in the individual;
- *False dichotomy questions*: they are closed questions in which both of the alternatives are erroneous.

This subdivision is, however, arbitrary and it has not been included in the manual (Gudjonsson et al, 2016).

At the end of the testing phase, the examiner can analyze a total of 12 indices (Gudjonsson et al, 2016):

1. *Immediate recall (IR).* It represents the quantity of salient information remembered. It gives an insight into the level of attention, concentration and mnemonic capacity of the individual. Each corrected remembered segment of the story counts 1 point, while the partially evoked concept counts 0.5 points. The highest possible score is 40.
2. *Distortions (D1)*. It measures the changed details of the elements in the story.
3. *Inventions (I1)*. It measures the introduction of a new element in the story.
4. *Confabulation 1 (CT1).* It's a score derived from the sum of the indices of Distortions and Inventions. It represents the difficulty of the individual in the recall of memories and therefore in the elaboration of the memory. Indeed,

individuals tend to substitute details that are not well remembered with imaginative details that they believe to have happened.

5. *Delayed recall (DR).* It reflects the number of details retained after an interval of time (50 minutes). The assignment of scores follows the same criteria of the Immediate recall index.
6. *Distortions (D2).* It measures the changed details of the elements in the story.
7. *Inventions (I2).* It measures the introduction of a new element in the story.
8. *Confabulation 2 (CT2).*
9. *Yield 1.* It denotes the number of affirmative answers to the 10 suggestive questions. Each affirmative answer counts 1 point. The highest score is 15.
10. *Yield 2.* It represents the number of affirmative answers to the 10 suggestive questions given after the examiner's negative feedback. As the Yield 1 index, the highest score is 15.
11. *Shift.* It indicates the number of times the individual changes its own answers subsequently the examiner's negative feedback. Each change of answers counts 1 point. The highest score is 15.
12. *Total suggestibility.* It's the total index of suggestibility: it derives from the sum of the indices Yield 1 and Shift. The highest score is 35.

The Gudjonsson Suggestibility Scale has both forensic and research aims.

On one hand it can be a useful instrument for detecting the attainability of witness statements in the forensic field of testimony, by identifying highly suggestible witnesses during oppressive police interrogations (Drake, Bull, & Boon, 2008); on the other hand, it can be a tool for research purposes to investigate the trait of suggestibility in the individual.

1.1.1.2. Cognitive, social and interpersonal factors associated with suggestibility

In the *Handbook of The Psychology of Interrogations and Confessions* (Gudjonsson, 2003), Gudjonsson found empirical evidence of correlation between IS and cognitive, social and interpersonal factors. Hereafter are reported the significant correlations that the author found in most of his studies and that are being replicated in more recent studies, with the aim to produce a more robust knowledge about this manifold construct and to validate the IS model.

- *IQs below the average and high suggestibility.*
  Gudjonsson reported a negative correlation between IS and intellectual functioning. However, it appears that the score in suggestibility is highly affected by range effects: subjects with IQs above the average exhibit a suggestibility level comparable to those with average IQs. Whereas, individuals characterized by a notably below average IQs, exhibit a higher degree of suggestibility. (Gudjonsson, 2003). The study conducted by Tully and Cahill (1984) supports the existence of the mentioned range effect: they found a correlation of − 0.69 between intelligence (measured by Raven's Coloured Matrices and the Crighton Vocabulary Test) and suggestibility (measured by the GSS-1). The markedly high correlation is derived from the fact that they recruited 30 learning disabled with an IQ score lower than 50 (and only 15 normal score subjects). Recent studies have found the same negative correlation (Gudjonsson & Young, 2021; Giostra & Vagni, 2024; Polczyk et al., 2024).
- *Memory quality below the average and high suggestibility.*
  A similar negative correlation affected by the range effect has been found between verbal recall on the GSS-1 and the GSS-2 and suggestibility scores (Gudjonsson & Clare, 1995; Sharrock & Gudjonsson, 1993). Memory and intelligence, nonetheless, seem to separately contribute to the interviewee's suggestibility: they contribute both individually and jointly to the variance in suggestibility (Sharrock & Gudjonsson, 1993). Recent empirical studies have observed analog consistent correlations (Polczyk et al., 2024; Biondi et al., 2020). In fact, verbal memory (Immediate Recall index) seems to be a better predictor of IS than global cognition (MMSE global score) (Zangrossi et al., 2020).
- *High levels of anxiety and high suggestibility.*
  High levels of trait anxiety are associated with high levels of suggestibility (Gudjonsson, 2003). However, studies have shown that state anxiety is more relevant than trait anxiety. By administrating the STAI questionnaire (Spielberger et al., 1983) before and after the GSS administration, they found a significant

correlation between the results in Shift and Yield 2 scores and the second STAI (Gudjonsson, 1988).

Recent findings were consistent with Gudjonsson's findings that state anxiety plays a stronger role than trait anxiety (Wong et al, 2024).

- *Sleep deprivation and high suggestibility.*

  Sleep deprivation reduces the mnemonic capacity and increases the vulnerability to suggestions. By impairing the sustained attention and the memory consolidation phases, the compliance during the interrogation increases alongside the difficulty in the individual in distinguishing between true and suggestive memories (Blagrove et al., 1994). Empirical evidence and meta-analyses continue to consistently report the detrimental effects of sleep deprivation (Kassin et al., 2018; Newbury et al., 2021).

- *Avoidance coping strategies and high suggestibility.*

  According to the subdivisions of methods of coping (Billings & Moos, 1981), Avoidance coping strategies, referring to a deliberate avoidance of engaging in a critical evaluation, have a significant relationship with heightened suggestibility, whereas the active-behavioural and active-cognitive methods are implemented by subjects that are more resistant to suggestions. While the non-suggestible coping strategies individuals involved a critical evaluation of each question and a problem-solving action, the suggestible group gave answers that seemed plausible and consistent with external cues. Similar correlation patterns among coping strategies were found in a recent study that evaluated children (Vagni et al., 2025).

- *External locus of control and high suggestibility.*

  An individual characterized by an external locus of control, the belief that outcomes are influenced by factors beyond personal control, tends to be more susceptible to suggestive influences, as suggested by the positive correlation between the Yield 1 score and the Total suggestibility score (Gudjonsson & Lister, 1984; Baxter & Bonn, 2000). New findings corroborate the higher propensity to produce false confessions for individuals exhibiting an external locus of control (Douglass et al., 2019).

- *Low self-esteem and high suggestibility.*

Sensations of helplessness and perceived inefficacy play a crucial role in enhancing suggestibility. Hence, a negative correlation between self-esteem and suggestibility is expected. In particular, in two studies (Gudjonsson & Singh, 1984; Gudjonsson & Lister, 1984) the authors found a significant negative correlation between self-esteem scores and the Shift score. However, more recent studies have found conflicting results: while comparative studies report an influence of self-esteem on suggestibility, correlational studies fail to show this relationship. This is supported by the hypothesis of a possible non-linear effect of self-esteem on confession decisions (Douglass et al., 2019).

- *Social desirability and high suggestibility.*

  Social desirability is associated with both compliance and suggestibility. In a study Gudjonsson found a small yet significant correlation between suggestibility and the "lie-scales" measured by the EPQ (Eysenck & Eysenck, 1975) and the Marlowe-Crowne scale (Crowne & Marlowe, 1960). Significant positive associations between social desirability and Shift scores were observed among the elderly population (Biondi et al., 2020).
- *Younger age and high suggestibility.*

  Gudjonsson found no significant relationship between age and suggestibility in the free recall and yield scores (Gudjonsson & Singh, 1984), however, various studies markedly exhibit the greater sensitivity that children display to interrogative pressure (Ceci & Bruck, 1995). The focus on younger age groups in suggestibility research has intensified in recent studies, acknowledging age as a critical factor affecting cognitive strategies and responses to social pressure. (Santirocchi et al., 2025; Vagni et al., 2025).

Nonetheless, other constructs have been firstly investigated in correlation with high suggestibility by Gudjonsson, but no recent studies have been carried out.

- *Low assertiveness and high suggestibility* (Gudjonsson, 1988).
- *Impulsivity and high suggestibility* (Gudjonsson, 1984).
- *Suspiciousness and high suggestibility* (Gudjonsson, 1988).
- *Field dependence and high suggestibility* (Singh & Gudjonsson, 1992).

Although it is considered a stable individual disposition, situational factors, such as the interviewer's behaviour, play a crucial role:

- *Interviewer's behaviour.*

  Baxter & Bonn (2000) investigated the role of the attitude of the interviewer while administrating the GSS 2. They subdivided the participants based on the friendly, firm or stern behaviour. The results showed highly significant differences between the three different conditions in Yield 2 and Shift scores. They interpreted the results as a "linear increase in the psychological distance between the interviewer and the interviewee" (Baxter & Bonn, 2000, p. 760). Similar results have been found in a study conducted by Dukala & Polczyk (2014) that compared elderly participants with young adults. By subdividing the participants based on the friendly or abrupt behaviour of the interviewer, a significant difference emerged: the abrupt behaviour led to increased likelihood of changing their answers after receiving negative feedback (Shift score), particularly among the elderly.

  Similarly, Wong et al (2024) found a significant difference in the GSS1 scores among participants in a supportive interviewer behaviour condition and individuals in a non-supportive and exposed to post-event misinformation condition. Indeed, interviewees in the second condition were more prone to confabulation or false memories. However, overall, the study highlighted the crucial role of individual differences. Consistent with Gudjonsson and Clark's theoretical framework, individual differences were stronger predictors of suggestibility, although it should not be negligible the role that the interviewer's behaviour exhibits.

1.1.2. Loftus: the *Experimental approach*

The *Experimental approach*, whose lead author is Loftus, has the objective to discover the conditions that affect the verbal accounts of witnesses.

The definition that Powers, Andriks and Loftus (1979) gives to Interrogative suggestibility states: "the extent to which they (people) come to accept a piece of post-event information and incorporate it into their recollection" (p. 339).

Loftus & Schooler aim to enrich the previously defined model of Gudjonsson & Clark by addressing the central cognitive mechanism of *Discrepancy detection,* that explains the mechanisms by which individuals accept and incorporate into their memory inconsistent information (Gudjonsson, 2003). In accordance with this mechanism, they state that "recollections are most likely to change if a person does not immediately detect discrepancies between post-event suggestions and memory for the original event (Schooler & Loftus, 1986, pp. 107–108).

Two main factors contribute to Discrepancy detection:

1. The *strength* of the original information in memory;
2. The *manner* in which the post-event suggestion is influenced.

Loftus introduces the construct of *Misinformation effect*, one of the most influential findings in experimental psychology. It refers to the problem of misleading post-event suggestions or inaccurate information that could be introduced after an eyewitness event and are highly likely to contaminate eyewitness memory (Ridley, 2013).

Being one of the most reliable findings, the misinformation effect raises concerns about the effectiveness and accuracy of eyewitness testimony: merely suggested details could result in highly elaborate false memories (Ridley, 2013).

Another core concept of Loftus's research is the *Post-Event Information (PEI)*, that explains the impact of "misleading questions" on the memory recall of witnessed events. Misleading questions have a detrimental effect on memory retrieval: inaccurate information can become incorporated into or overwrite the original memory trace, producing distortions in interviewee's responses and in the retrieval of memory (Pino, 2015).

In 1978, Loftus, Miller and Burn employed a three-phases paradigm to investigate the impact of misleading information (Ridley, 2013; Chrobak & Zaragoza, 2013).

1. *The witnessing of an event.*

   Firstly, the participants watched a slide-sequence of an auto-pedestrian accident at a yield sign.

2. *Introduction of post-event information.*

   Secondly, participants in the "misled condition" were asked a suggestive question referencing a yield sign instead of a stop sign. Specifically, they were asked: "Did another car pass the red Datsun while it was stopped at the stop sign?" (Loftus et al., 1978, p. 22). On the other side, participants of the control group were not misled.

3. *Evaluation of the original event recollection.*

   Finally, a forced-choice test was executed: participants had to identify the correct traffic sign of the slide-sequence accident (they were required to choose between a stop or yield sign).

Results highlighted the introduction of false memories and distortions caused by post-event misinformation: whereas 75% of the control group correctly identified the stop sign, only 41% of the misled group selected the right choice (Ridley, 2013).
This paradigm and its parallel versions have been widely replicated in various recent studies (e.g. Raghunath et al., 2021; Holmes et al., 2024; Wiechert et al., 2025), aiming to validate the robustness of the construct misinformation effect and to extend further studies on its underlying mechanisms.

Concerning the *Individual differences* approach, Loftus & Schooler conclude: it "represents a formidable attempt to make sense of a multi-faceted phenomenon. The emphasis on the role of individual differences in interrogative suggestibility complements the more experimental approach to the influence of post-event suggestions. [...] At the same time the individual differences approach is relatively devoid of detail regarding the precise cognitive mechanisms that may mediate the incorporation of post-event suggestions. Throughout their discussion, Gudjonsson and Clark hint at plausible mechanisms without explicitly describing them" (Schooler & Loftus, 1986, p. 107).
They interpreted the salient key points of the model of Gudjonsson & Clark by relating them to the Discrepancy detection mechanism:

- Regarding *Uncertainty*: "Uncertainty facilities suggestibility by reducing the likelihood that a witness will experience a discrepancy between the original event and the subsequent suggestion" (p. 107).
- Regarding *Interpersonal Trust*: A suspicious cognitive set leads interviewees to examine the interrogator's questions with more attention, enabling them to detect potential inconsistencies between their own recollection and what has been suggested to them later (Gudjonsson, 2003).
- Regarding *Negative Feedback*: A reduction in confidence in the interviewees and an increased level of anxiety makes them less likely to compare the suggestions with their own recollection (Gudjonsson, 2003).

Hence, while Gudjonsson & Clark stated that Interrogative suggestibility is mediated by various cognitive and personality variables, Loftus & Schooler postulated that the mechanism of discrepancy detection by itself mediates IS.
The latter integration of the distinct approaches described allows to further acquire a more robust theoretical understanding of the construct of Interrogative Suggestibility.

1.2. Forensic implications of suggestibility in healthy elderly individuals

The theoretical approaches described have implications for the accuracy of eyewitness testimony among individuals predisposed to suggestibility. Certain populations, however, appear to be more vulnerable, including healthy older adults. The following paragraphs focus on this cohort, outlining their cognitive and memory functioning and how these mechanisms are related to suggestibility.

1.2.1. Cognitive functioning in natural aging

For the purpose of this dissertation that considers only *healthy* elderly individuals, its definition is hereby needed. A systematic review on the definition of healthy aging (Menassa et al, 2023) underscores its multidimensionality and complexity. The authors identified two dominant approaches in scientific literature. The first approach emphasizes the absence of disease and focuses on health outcomes. On the other hand, the second approach displays a holistic concept of healthy ageing, in accordance with the definition provided by the World Health Organization (WHO): "the process of developing and maintaining the functional ability that enables wellbeing in older age" (Rudnicka et al., 2020).

Therefore, in this dissertation, the term *healthy* refers primarily to the first approach: the participants needed to be free from any dementia syndromes or psychiatric disorders.

Given these considerations, however, it is markedly important to take in mind that even in healthy ageing it is physiological to observe a decaying in cognitive abilities.

This starts with reduced encoding of incoming information due to the decreasing functioning of sensory organs. For example, the physiological changes that the eyes encounter: the increased rigidity of the iris and the lens and the subsequent reducing of pupil diameter (Toglia et al., 2014).

From a neuropsychological perspective, the psychology of memory literature highlights the association between natural aging and memory performance. Structural and functional changes in the brain, particularly the diminished synaptic plasticity and alterations in neural connectivity, cause changes in memory function. Furthermore, aging processes are associated with a decreasing in attention, working memory, executive control, decision-making processes.

Misinformation research (Loftus et al., 1978) has been focused on source monitoring, one of the functions associated with frontal lobes, which are notably among the earliest regions to exhibit age-related decline. As a result, the elderly's ability to distinguish between internal and external memory contents and the ability to identify the origin of a memory are more limited (Toglia et al., 2014).
Referring to the phases implied in the *Misinformation effect paradigm* (Loftus et al, 1978), older adults are likely to be less able to discern whether information was encoded during phase 1 (original information) or phase 2 (misleading information). Indeed, a meta-analysis found that older adults are more susceptible to misinformation (moderate effect r = 0.35) compared with younger adults (Toglia et al., 2014).
When experiencing difficulties with source monitoring, older adults tend to compensate by anchoring their memory on available retrieval cues, enhancing the probability of falling for misleading questions (Toglia et al., 2014). Indeed, numerous replications of this approach have demonstrated that a sizable proportion of participants incorporate misleading information into their memory for the event detail compared with control groups who do not receive misleading information (Davis & Loftus, 2007). This effect has also been demonstrated in ecologically valid field settings, such as message therapy (Mueller-Johnson & Ceci, 2004) and a museum visit (Loftus et al, 1992).
These findings can be referred to the *Fuzzy-trace theory (FTT)* (Brainerd & Reyna, 2002; Reyna & Brainerd, 1995), a dual-process that distinguished between *verbatim memory*, representations that preserve the surface details of target experience and *gist memory*, representations that preserve their semantic bottom-line meaning. Evidence shows that older adults tend to rely on *gist traces* to a greater extent than younger adults, setting aside the surface details of target experience. This shift of reliance from verbatim memory towards gist memory leads to FTT's predictions about an increase in false memories from early to late adulthood (age 65 onward).

1.2.2. Interrogative Suggestibility in healthy elderly individuals: studies involving the Gudjonsson Suggestibility Scale

Given the aforementioned characteristics of cognitive functioning in healthy older adults compared to younger adults, it is reasonable to expect higher levels of interrogative

suggestibility among the former group.
However, it is only in recent years that the elderly population has received more attention when investigating IS. Four studies have been used the Gudjonsson Suggestibility Scale to directly measure the IS construct (Polczyk et al., 2004; Mueller-Johnson & Ceci, 2004; Dukala & Polczyk, 2014; Biondi et al., 2020):

1. Polczyck et al (2004) compared young adults (mean age = 22.3; standard deviation = 3.3; range = 18-35) with older adults (mean age = 64.1; standard deviation = 9.5; range = 49-88) using the GSS-2. Older adults exhibited higher scores on the Yield scale. Additionally, the memory performance assessed by the Wechsler memory scale (WMS) and the Memory Assessment Clinics Self-Rating Scale (MAC-S) seems to be a significant predictor of Yield scores.
2. Mueller-Johnson & Ceci (2004), by comparing younger (mean age = 20.2; standard deviation = 1.12; range = 18-20) and older adults (mean age = 76.4; standard deviation = 7.85; range = 65-93) and administering the GSS, observed a general tendency for elderly individuals to be more susceptible to suggestive questions.
3. Dukala & Polczyk (2014) conducted a study subdividing participants in two groups: young adults (mean age = 23; standard deviation = 2.77; range: 16-29) and young elderly individuals (mean age = 66.8; standard deviation = 2.17; range: 64-74). The two experimental conditions were characterized by the interviewer demeanor: either friendly or abrupt when administering the GSS-2. The results showed that under the abrupt interviewer condition, elderly individuals exhibited significantly higher Shift scores compared to young adults, while under the friendly interviewer condition they were comparable among the two age groups. Additionally, the elderly group exhibited a higher Yield score than young adults.
4. Biondi et al (2020) further investigated the construct of IS in the elderly population by sampling older individuals (aged 65 years and older) and splitting the participants into age classes: late adults (mean age = 59.64; standard deviation = 2.79; range = 55-64); young elderly (mean age = 69.10; standard deviation = 3.01; range = 65-74); elderly (mean age = 78.14; standard deviation = 2.60; range = 75-85). With the purpose to delve deeper into the associations between IS and

emotive/affective and cognitive variables, they confirmed various of their hypotheses. Firstly, the oldest group exhibited poorer performance levels across all indices of the GSS-2. Secondly, low levels of memory and intelligence were correlated with higher Yield scores. Furthermore, the results indicated the influence of affective and social factors on IS: the analysis reported a positive relationship between Shift scores and anxiety, alongside a negative relationship between Shift scores and self-esteem, supporting the original studies of Gudjonsson (2003). Additionally, they observed a positive correlation between Shift scores and social desirability among the young elderly group.

In conclusion, these studies all agree on one finding: older adults exhibit greater tendency to be misled by misleading questions, as indicated by the Yield index and the overall Total Suggestibility score. Also, this corroborates the evidence that even *healthy* elderly individuals are more predisposed to enhance suggestibility trait.

1.2.3. Mistaken eyewitness identification and false confessions: appropriate interview protocols

According to data from The Innocence Project, among 325 examined cases that led to wrongful convictions, 72% involved mistaken identification, while 27% constituted false confessions (Sartori, 2021). It is important to note that these data are not strictly specific to old adults.

However, the physiological and neuropsychological declines observed in elderly individuals, combined with their heightened suggestibility, are more likely to render the elderly more vulnerable to mistaken eyewitness identifications and false confessions.

An old person that becomes eyewitness of a crime and decides to report to the police will be asked to start with a free narrative (*free recall*) and subsequently with a more structured recall marked by more specific questions (*cued recall*) (Toglia et al, 2014). Sometimes, they're also asked to identify the suspect. The usual approaches in the identification process include: *photospreads*, where witnesses are required to select suspects from a series of four to six photographs; *lineups*, involving the physical presence of four to six individuals; *showups*, in which witnesses assess whether a single individual or photograph corresponds to the culprit (Brainerd & Reyna, 2019). By relying on gists, as the Fuzzy-Trace Theory (FTT) paints, elderly witnesses are more likely to mistakenly identify innocent individuals when non-suspects share similar gist characteristics with suspects.

False confessions, on the other hand, are more related to individual factors, such as the predisposition to suggestibility, and the investigative context (Kassin, 2017). Indeed, interviewing techniques pose risks to the integrity of witness statements (Brainerd & Reyna, 2019). These include repeated questions, answer challenges, enforced answers, punishment, reward, false evidence, authority appeals (Brainerd & Reyna, 2019). Also, asking to agree or disagree about key events or to choose among events, rather than allowing to provide open-ended narratives are some features that may stimulate false memories. These latter techniques are the type of questions chosen for the Gudjonsson Suggestibility Scale, that thereby is likely to contribute to the false confession research. Given these considerations, tailored interview protocols should be developed to increase the probability of accurate and reliable testimony.

Best practice investigative interviews recommend the following guidelines: firstly, building rapport through neutral conversation; secondly, establishing ground rules, such as allowing the interviewee to indicate uncertainty; thirdly, encouraging free recall without interruptions; additionally, using open-ended questions before closed ones to encourage detailed recollections; finally, closing the interview positively by summarizing and verifying information, which may prompt further memory retrieval (Toglia et al., 2014). The PEACE model (Bull, 2023) and the Cognitive Interview (CI) (Holliday et al., 2009) have proven to be reliable techniques that and thereby enhance the integrity of eyewitnesses. Furthermore, a modified version of the latter protocol (MCI) has shown effective results in the elderly witness testimony, by reducing the impact of misleading suggestions (Holliday et al., 2012). Specifically, the MCI protocol comprises four retrieval strategies grounded in memory theory (Tulving & Thomson, 1973; Tulving, 1974): reinstating the mental context of the event, encouraging the reporting of all recalled details and requesting recall in reverse order.

In conclusion, when encountering an elderly individual in the legal context, the notion that general cognitive abilities decline in older age is justified by research evidence.

However, it is important to emphasize that not all elderly individuals are suggestible just because of age and not all elderly people exhibit suggestibility to the same degree. In fact, suggestibility, understood as a construct that combines both trait characteristics and situational influences, can be heightened in certain elderly individuals who possess a "susceptible" predisposition. This variability is influenced by cognitive factors, such as memory and intelligence, as well as emotive and affective variables, such as self-esteem and anxiety, which together contribute to the multifaceted nature of suggestibility in older adults.

Summary

This chapter introduced the construct of Interrogative Suggestibility (IS). By focusing on the two main theoretical approaches (the individual differences approach (Gudjonsson & Clark, 1986) and the experimental approach (Schooler & Loftus, 1986), IS appears to be a situation bound dynamic process mediated by various cognitive and personality variables that can be exacerbated under certain conditions.

The theoretical approaches described have implications for the accuracy of eyewitness testimony among individuals predisposed to suggestibility. Indeed, certain populations appear to be more vulnerable, including healthy older adults.

The physiological cognitive functioning decline in natural aging, with particular attention to episodic memory and source monitoring, contributes to consider healthy elderly individuals as more vulnerable to exhibit greater tendency to be misled by misleading questions.

This vulnerability is also sustained by recent evidence that uses the Gudjonsson Suggestibility Scale (GSS) to measure Interrogative Suggestibility.

Therefore, these considerations need to be taken into account when interviewing elderly individuals in the forensic world, especially regarding eyewitness testimony and false confessions. Hence, some recommendations have been introduced for police officers and juries to have a special attention to this population, without overlooking the fundamental notion that high suggestibility is indeed more likely in older adults and under certain stressful situations, but it is also a trait observable across all individuals.

CHAPTER 2: THE *EYE* AS A WINDOW TO THE *BRAIN:* RESTING STATE EEG AND PUPILLOMETRY

In the age-old expression "the eye is the window to the soul" there may be more to it than meets the eye: pupil responses reflect intrinsic autonomic activity even in the absence of directed tasks and provide a window into ongoing brain function. Indeed, electroencephalography and pupillometry both serve as effective techniques for assessing cognitive states, even during resting-state conditions.

Recent research (e.g. Montefusco-Siegmund et al., 2022) has focused on the combined analysis of these two techniques emphasizing their co-modulatory relationship: pupil size being an indicator of arousal and brain rhythm monitoring intrinsic fluctuations.

This chapter focuses on the EEG and pupillometric techniques that have been employed for this study and their underlying mechanisms, by also displaying the typical results that scientific literature displays in healthy elderly individuals.

2.1. Resting state EEG: brain rhythms

The electroencephalography traces back to the pioneering work of Hans Berger (1929). By placing electrodes on the frontal and occipital cortices, he identified and further described a rhythmic brain activity oscillating at approximately 10 Hz, particularly active during relaxed wakefulness: the alpha waves. Since Berger's groundbreaking discovery that these fluctuations in the human EEG might be linked to mental functions, EEG has been established as a fundamental tool for investigating human activity (Da Silva, 2023). The brain waves detected by EEG originate primarily from the synchronized electrical activity of large ensembles of cortical pyramidal cells, which are aligned perpendicularly to the cortical surface (Da Silva, 2023). These neurons generate fluctuating transmembrane ionic currents, predominantly postsynaptic potentials, which create extracellular current dipoles. When many neurons activate synchronously, these dipoles summate to produce measurable electrical fields which are detected by the EEG at the scalp surface (Da Silva, 2023). The EEG system amplifies and further filters these signals, which are subsequently digitized and analyzed, revealing their oscillatory patterns (Da Silva, 2023).

These multiple oscillations exhibit characteristic frequency bands, related to specific functional states of the brain (Da Silva, 2023).

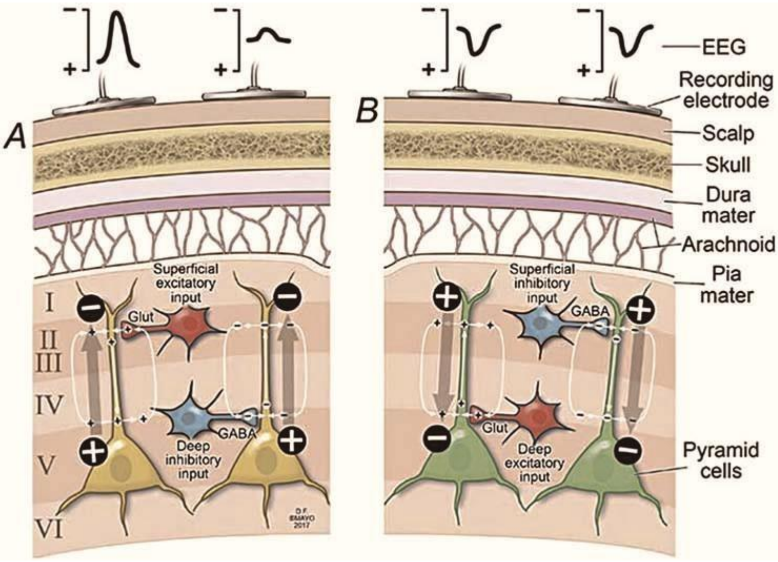


Figure 3. *The figure displays the neurophysiological origin of scalp-recorded EEG potentials. The process is attributable to the spatial summation of the current dipoles generated by vast assemblies of cortical pyramidal neurons, varying in magnitude, polarity and orientation, especially in cortical layers IV and V. (Tatum et al., 2018).*

Indeed, historically, brain oscillations have been grouped into bands, according to their frequency activity, or number of cycles per second. The role of each band has been largely documented: each brain rhythm is associated with performance in several different cognitive tasks, as briefly summarized in the following table (Da Silva, 2023; Klimesch et al., 1999). For calculating the amount of distribution of signal power over the distinctive frequencies, the Power Spectral Density (PSD) is the crucial parameter used.

FREQUENCY BAND	***FREQUENCY RANGE (Hz)***	***AMPLITUDE RANGE (µV)***	***ASSOCIATED COGNITIVE FUNCTIONS***
DELTA	1-4 Hz	20-200 µV	Deep sleep, unconsciousness
THETA	4-8 Hz	10-100 µV	Memory encoding, focused attention
ALPHA	8-13 Hz	20-60 µV	Relaxed wakefulness, inhibition control
BETA	13-30z	5-20 µV	Active thinking, sensory-motor processing
GAMMA	>30 Hz	1-10 µV	Higher cognitive functions, memory binding

However, spontaneous activity of the brain is also of considerable interest due to its intrinsic functional role.

Spontaneous brain activity, also referred to as *endogenous* or *intrinsic* brain activity consists of dynamic patterns of cortical and subcortical spontaneous activity that emerge during resting periods (Raichle, 2011; Buckner et al, 2013). Traditionally called *idling state*, it represents a state characterized by no processing of sensory information nor motor output. Although it has been classically misconceived with noise, it has been persistently shown patterns of long-range coordination between distant brain regions (Fox & Raichle, 2007; Chino et al., 2024).

In fact, the brain is constantly active even without engagement in task-related activities or without receiving sensory stimuli. Evidence shows minimal variance between resting-state conditions and task-related periods, highlighting the continuous and consistent high energy consumption that the brain needs. As a matter of fact, most of the brain energy is spent on resting potentials (approximately 60%), while spikes account for about 10%. The remaining 30% that is not spent for electrochemical signaling, is used for housekeeping functions, such as protein synthesis, gene expression and so on (Raichle, 2011; Pezzulo et al, 2021).

Most studies have used functional magnetic resonance imaging (fMRI) as a measure to study resting state patterns. Specifically, a more intense activity during resting state in a specific network has been predictive of better performance in the cognitive domain, being interpreted as a sign of renormalization of patterns of oscillatory activity observed during ongoing cognitive processes. Therefore, brain activity during active cognitive efforts is directly related to resting state conditions (Stevens & Spreng, 2014).

However, there is a gap in the literature concerning the research of the relationship between resting state and cognitive abilities with the technique of EEG.

Various studies provide evidence supporting the crucial role of alpha activity as the pivotal brain rhythms in the resting state condition.

For example, studies have explored alpha activity in resting state in relation to attentional breadth (Pitchford & Arnell, 2019), temporal attentional tasks (MacLean et al., 2012) and working memory (Bazanova & Vernon, 2014; Tuladhar et al., 2007).

2.1.1. Typical RS rhythm pattern in healthy elderly individuals

In normal aging, it is expected to observe a decline in alpha power, especially in parietal, occipital and temporal regions. (Babiloni et al., 2006; Garcés et al., 2013; Zhong & Chen, 2020). Particularly, compared to younger adults older adults exhibit a significant reduction in individual alpha peak frequency (IAPF), which is the frequency within the alpha band at which the highest power peak is observed (Scally et al., 2018).

In contrast, other studies observed an increase in alpha power in normal aging (e.g. Ranasinghe et al., 2025). A systematic review of Chino et al. (2024) revealed a robust relationship with cognitive capacity (highly associated with better performance in executive functions, perception and fluid intelligence (Clark et al., 2004; Grandi et al., 2013; Lopez-Sanz et al., 2016; Trammel et al., 2017; Choi et al., 2019; Stacey et al., 2021).

However, other frequency bands seem to also be related to age effects in resting state conditions. For example, a decrease of delta and theta rhythm in the occipital cortex alongside an increase beta power (Kumral et al., 2019; Zhong & Chen, 2020).

In summary, increased alpha power but reduced theta power in the resting condition is associated with better cognitive performance. These may represent compensatory neural mechanisms that support cognitive resilience throughout the aging process (Ranasinghe et al., 2025).

2.2. Resting state pupillometry: pupil size

Pupillometry, the measurement of pupil size and its fluctuations, is a valuable and widely recognized non-invasive tool for monitoring brain activity, cognitive states, arousal levels, alongside spontaneous neural processes.

The pupil encounters distinct reactions in response to three distinct types of stimuli (Mathôt, 2018):

1. *Pupil light response (PLR):* the pupil constricts in response to brightness. Being primarily modulated by light stimuli, the pupil regulates the amount of upcoming light by dynamically constricting or dilating, with diameters ranging from 2 mm, under the brightest conditions, to approximately 8 mm, in the darkest environments.
2. *Pupil near response (PNR):* the pupil constricts near fixation and dilates when looking at a far-away object.
3. *Psychosensory pupil response (PPR):* the pupil dilates in response to increased cognitive activity, particularly during elevated arousal and mental effort. The PPR can manifest as a rapid but brief pupil dilation as a part of an orienting reaction to stimuli, but also as a more sustained dilation that reflects prolonged increase in arousal.

Spontaneous fluctuations in pupil size share similarities with the psychosensory response, except that they occur without direct external stimulation. These changes are called *Hippus* or *Pupillary unrest*. The first term refers to periodic fluctuations, while the second term indicates any kind of spontaneous fluctuations. When awake and alert, pupils' individuals are relatively large and stable. However, as they become tired, the pupils became smaller (Lowenstein et al., 1963). Similarly, Bouma & Baghius (1971) observed that pupillary unrest was most common during periods without a specific task, likely due to drowsiness, whereas a mental task significantly reduced these fluctuations. These findings indicate that spontaneous pupil-size fluctuations are associated with activity in the locus coeruleus (LC), a key hub region of ascending arousal systems that plays a crucial role in regulating global arousal states, as well as more fine-tuned responses to salient stimuli (Papesh & Goldinger, 2024).

Indeed, gathered evidence supports the crucial role of the locus coeruleus-norepinephrine (LC-NE) system towards arousal-mediated pupillary response. Particularly, the dynamic patterns of LC-NE system activation regulate high-cognitive functions. By sending dense efferent projections to most cereal regions, the LC enables to regulate both local patterns and brain-wide communication among distinct functional networks (Poe et al., 2020; Papesh & Goldinger, 2024).

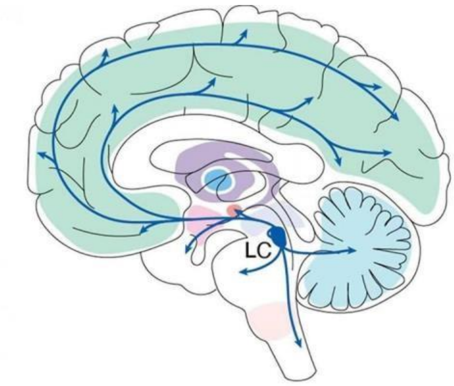


Figure 4. *Anatomy of the LC-NE system. The output projections originating from the LC nucleus are depicted by the connecting lines. The shaded regions denote major subregions that provide afferent input to the LC. (Breton-Provencher et al., 2021).*

Under arousal, NE is broadly released across both cortical and subcortical regions, where it interacts with multiple classes of adrenoreceptors that differ in their functional characteristics, spatial localization and binding affinities for NE (Berridge & Waterhouse, 2003; Papesh & Goldinger, 2024). Commonly classified into alpha1-, alpha2-, and beta-adrenoreceptors, each of these receptor subtypes modulates neural excitability and synaptic plasticity in distinct ways.

LC regulates arousal through alterations in its own firing dynamics (Papesh & Goldinger, 2024):

- *Phasic activity*: Transient activity characterized by burst rates of approximately 8-10 Hz. It is typically triggered by salient (novel, unexpected, goal-relevant or rewarding) stimuli;
- *Tonic activity*: Baseline activity; defined by slower rates of 1-6 Hz. It refers to a more sustained, background level of neural discharge. Elevated tonic LC output is strongly associated with heightened wakefulness and global arousal.

The mechanisms underlying cognitive activity-related modulations in pupillary dynamics have been elucidated only recently. Nowadays, it is widely acknowledged that both cholinergic and noradrenergic neuromodulatory systems contribute to pupillary fluctuations that track arousal levels (Reimer et al, 2016; Papesh & Goldinger, 2024).

The robust link between the LC-NE system and the pupil was at first demonstrated in monkey studies, examining resting-state recordings of pupil size and LC neural activity (Rajkowski, 1993): heightened LC firing corresponded with pupil dilation (Papesh & Goldinger, 2024).
The locus coeruleus involvement in regulating pupil size is also provided by the stimulation of the Vagus Nerve Stimulation (VNS): the VNS projects to the Nucleus of the Tractus Solitarius (NTS), which in turn sends projections to the LC as well as to other regions.
The pathway underlying the pupillary light and dark reflexes include a sympathetic branch, which mediated pupil dilation through excitatory input to the iris dilator muscles, and a parasympathetic branch, which mediated pupil dilation through excitatory input to the iris sphincter muscles (Loewenfeld & Lowenstein, 1993; Papesh & Goldinger, 2024). Lesion studies have suggested a coordinated interaction between both branches on regulating pupil diameter: diminished patterns of LC-mediated pupil dilations have been encountered when disrupting either the sympathetic or parasympathetic pathways (Liu et al, 2017; Papesh & Goldinger, 2024).

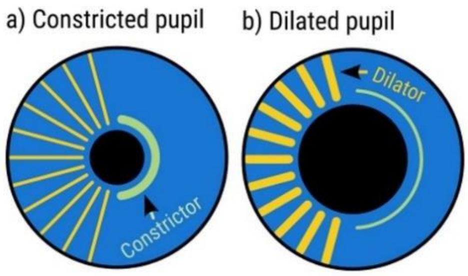


Figure 5. *Sympathetic-driven contraction of the iris sphincter muscle resulting in the constriction of the pupil by tightening the inner side of the iris (a). Parasympathetic-driven activation of the iris dilator muscle inducing pupil dilation by pulling the inner side of the iris outward (b) (Mathôt, 2018).*

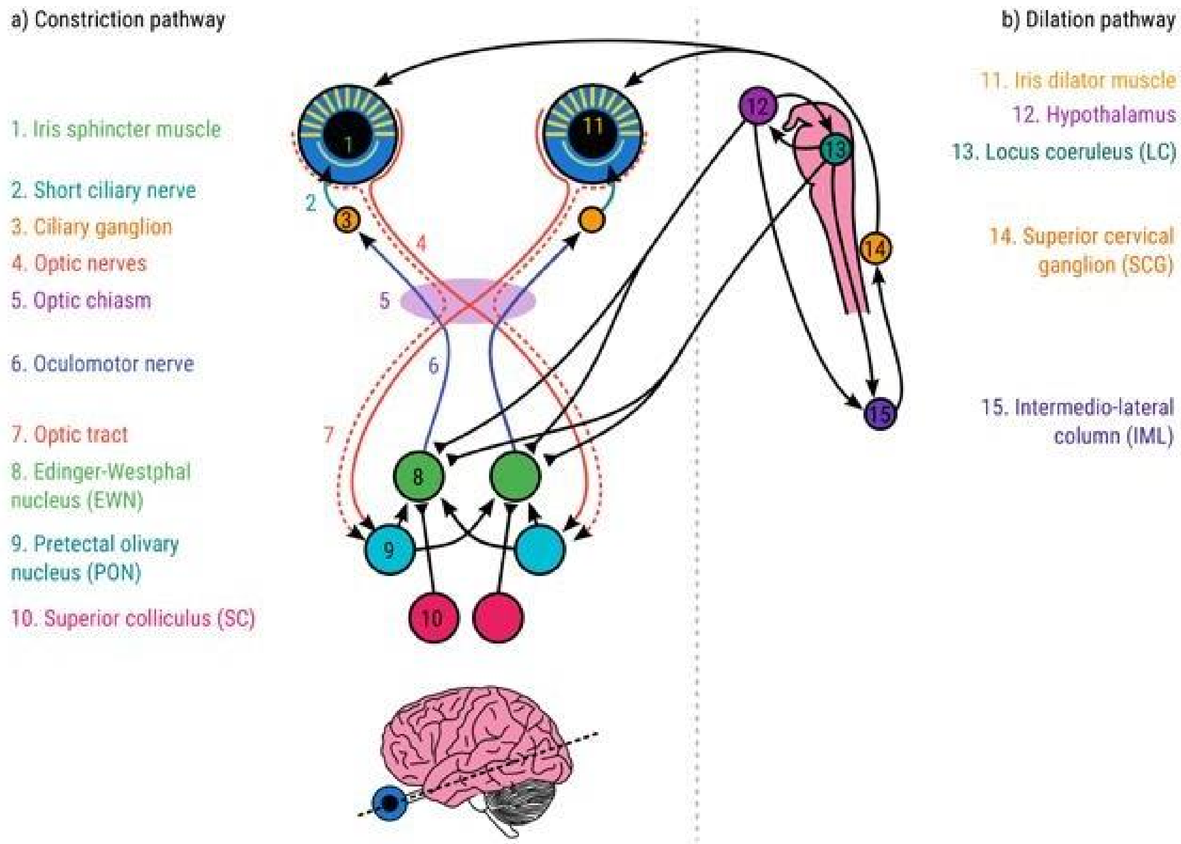


Figure 6. *The pupil constriction (a) and the pupil dilation pathways, parasympathetic branch (b) (Mathôt, 2018).*

2.2.1. Typical RS pupillometric pattern in healthy elderly individuals

In recent years, there has been a surge of focus in investigating how age-related alterations in the structural and functional integrity of the LC-NE system relate in cognitive decline, in particular in Alzheimer's Disease (Papesh & Goldinger, 2024; Betts et al., 2019; James et al., 2021), but also in normal aging.

In commonly observed normal aging, studies have shown that disrupted LC interactions with the frontoparietal network may underly the decrements in task-focused attention and distractor inhibition (Lee et al., 2018; Kennedy & Mather, 2019; Mather et al., 2020).

Age-related disruptions in the supply-demand equilibrium between cognitive demands and available neural resources. Demands exceeding supply, as it is clearly exemplified in normal aging, contribute to the reduced working memory capacity often observed (Schneider-Garces et al., 2010; Papesh & Goldinger, 2024). The alterations in the LC-NE system may involve an elevation in tonic arousal levels (Mather et al., 2020).

Representing compensatory mechanisms in response to the progressive loss of LN neurons, sustained tonic arousal may suppress phasic LC discharges (Papesh & Goldinger, 2024).
Core hallmarks of normal aging, such as failures to inhibit distractors and sustain focus attention, may be related to the elevated LC tonic activity that enables both task-relevant and task-irrelevant stimuli to utilize the available cognitive resources (Lee et al., 2018). Moreover, evidence reported that the overall decline in autonomic flexibility and neural modulation translated on a less dynamic resting-state pupil size variability (Aminihajibashi et al., 2019).
Given these considerations, in healthy elderly individuals, we may expect a higher baseline pupil size derived by the elevated LC tonic activity and a less dynamic resting-state pupil size variability.
However, there is a further phenomenon that should be taken into account: the *senile miosis* process. This phenomenon is observed as a steady decline after the second decade of life, more pronounced under dim lighting (Lazar et al., 2024). Winn et al., (1994) reported an age-related reduction of approximately 0.043 mm per year in pupil diameter at a luminance of 9 cd/m^2. Typical aging processes such as iris stiffness, muscle degeneration, reduced photoreceptor density, alongside delayed photopigment regeneration and lens yellowing, contribute to the observed phenomenon.
In conclusion, in healthy elderly individuals, we might encounter a paradoxical combination: a structurally smaller baseline pupil size, due to the effect of senile miosis (Lazar et al., 2024), alongside a potentially elevated LC tonic activity that might increase baseline pupil size compared to younger adults (Lee et al., 2018; Mather et al., 2020). Therefore, a co-existence of these two phenomena may be present: although the maximum pupil size achievable may be smaller in healthy elderly individuals, the tonic arousal-related component could still be relatively elevated at rest, compared to younger adults.

2.3. EEG and pupillometry: physiological indicators of Cognitive Load

According to Cognitive Load Theory (CLT), Cognitive Load is defined as the workload imposed on the individual's finite cognitive resources to process and combine information required for a task (Sweller et al, 2019). The evaluation of metrics and their changes in this field of study depends on the tasks analyzed that often require various mental resources, such as attention, working memory, decision-making, along with task-specific knowledge.

Chakladar & Roy (2024) published a review that aimed to highlight the in-depth analysis of physiological methods used to evaluate cognitive load.

Alongside the physiological measures, they mentioned other metrics used in the assessment of the construct: Subjective measures, defined by the quantitative rankings of an individual's feelings; Performance measures, characterized by a person's performance during a task as the complexity of the task progressively increases.

However, they focused primarily on physiological measures, subdividing them further into brain activity-based measures and non-brain activity-based measures.

- *Brain activity-based measures.* Besides Electroencephalography (EEG), the most common type of metrics, other activity-based techniques are used, such as: Functional Magnetic Resonance Imaging (fMRI), Magnetoencephalography (MEG), Functional Near-Infrared Spectroscopy (fNIRS) and Positron Emission Topography (PET).

  The advantages highlighted in the review refer to their high-specificity and temporal and spatial resolution. However, researchers must contend with ethical concerns required by the instrumentation and the expensive and complex techniques.
- *Peripheral measures.* Further subdivided into:
  - a. *Cardiovascular activity*: Heart Rate (HR), Heart Rate Variability (HRV), Electrocardiography (ECG);
  - b. *Respiratory measures*: Respiration Rate (RR), Ventilation;
  - c. *Pupillometric and eye-movements metrics*: Blink Rate (blink duration and blink latency), Pupil size (mean diameter).

The authors emphasized their advantages of simplicity and cost effectiveness, but they take into account their main disadvantage: the high vulnerability to noise artifacts.

The majority of studies analyze cognitive load during a specific cognitive task. Its definition itself requires three concepts that are strictly related to a it:

1. *Intrinsic cognitive load*: induced by the inherent nature of the task (Cook et al., 2017);
2. *Extraneous cognitive load*: related to external factors (e.g. noise, time pressure; overall situation) (Cook et al., 2017);
3. *Germane cognitive load*: referred to the mental resources allocated within working memory as a function of experimental design and automation of schemas (Cook et al., 2017).

Given these considerations, the multimodal approach is commonly adopted, to ensure a more robust framework for real-time measurement of cognitive load.

The combined analysis of EEG and Eye-tracking activity, as conducted in the present thesis, is a multimodal analysis that has been validated and widely utilized, as demonstrated by the proportion of studies identified in the review conducted by Chakladar & Roy (2024), representing 15% of the total studies.

Indeed, electroencephalographic frequency power bands and pupil indices can be considered physiological indicators of cognitive load measured during cognitively demanding tasks.

On one hand, the most typical pattern to observe during a cognitive load task is a decrease in alpha activity alongside an increase in theta activity (Schapkin et al., 2020; Laufi & Longo, 2022). Specifically, frontal theta band is associated with mental fatigue and drowsiness and seems to increase in task difficulty (Borghini et al., 2014; Laufi & Longo, 2022). A suppression in the alpha-activity, primarily associated with parietal and occipital regions, seems to be linked with increments of task difficulty (Mazher et al., 2017; Puma et al., 2018; Laufi & Longo, 2022).

On the other hand, regarding pupil size, it is a well-stablished phenomenon that in response to increased arousal and mental effort pupil dilates (Stanners et al., 1979; Mathôt, 2018) and pupil size variability increases (Murphy et al., 2014; Podvalny et al., 2021).

2.3.1. Can we extend the *task-elicited* arousal state to a *resting* state?

Should we expect cerebral and pupillometric *arousal* pattern during resting states in individuals who are also characterized by an increase arousal in response to cognitively demanding task? So, should we except a reduced baseline alpha activity and a more dilated baseline pupil?

A recent study (Chen et al., 2025) supports the idea that cognitive load does not only manifest itself during an explicit attentional activity, as it was always studied, but also during resting states, extending the traditional concept of cognitive load to a more dynamic and intrinsic stance.

This study examined the association between the temporal variability of resting-state networks and working memory performance, by building a multivariate predicting model. Resting-state EEG data (five minutes, eyes-closed) were collected before the participants engaged in the working memory task (one hour). The EEG-based protocol combined with fuzzy entropy analysis to quantify the temporal variability of resting-state networks.

The assumption is based on the percentage of consumption of the brain's energy to support various functions that require approximately 80%. The task-related metabolic changes, on the other hand, typically account for 5% (Raichle & Mintun, 2006). Therefore, it comes natural to think that spontaneous activity during resting state conditions may offer valuable insights into the neural substrates underlying working memory.

In addition, the typical and intrinsic configuration of spontaneous activity exhibits cognitive relevance (Ito et al., 2017; Jiang et al., 2023). This finding suggests that individuals characterized by efficient resting-state networks tend therefore to show more efficient cognitive performance.

The study demonstrated that the temporal variability of cerebral networks in resting-state conditions reflect intrinsic functional dynamics significantly correlated to the working memory performance (WM) during cognitive tasks. In particular, connectivity among frontal, central and parietal lobes was significantly associated with working memory performance.

However, the authors, focusing on network patterns, did not take into account the power spectrum analysis of brain rhythms. In fact, they pointed out the crucial role of alpha oscillations in cognitive processes, including WM deployment (van Dijk et al., 2010), concluding that “it is crucial to further investigate the role of alpha oscillations in WM processes and the potential relationship between resting-state alpha activity and task-induced alpha modulation.” (Chen et al., 2025).

Analog considerations can be applied to baseline pupil size, representing a relatively understudied area in pupillometric literature.

One example derives from Tsukahara et al. (2016) that found a significantly bigger baseline pupil size correlated to a higher activity of the noradrenergic system. Even if it was not explicitly in the framework of cognitive load, it was congruent with it: the noradrenergic system regulates the arousal by releasing noradrenaline (NA), and therefore cognitive demanding tasks.

Aminihajibashi et al. (2021) found a significant correlation between baseline pupil size variability and working memory performance, but they failed to replicate previous studies that found an association between larger mean resting state baseline pupil size and higher WMC (Heitz et al., 2008; Tsukahara et al., 2016).

2.3.2. Pupillography: a promising tool to assess Cognitive Load

The analysis of pupil size oscillations, also referred to as *Pupillography*, has recently been employed to assess cognitive load.

As described above (see paragraph Resting state pupillometry: pupil size), pupil size is regulated by the autonomic nervous system: the sympathetic system drives pupil dilation, while the parasympathetic system regulated pupil constriction. Therefore, information about the balance between the two branches can be inferred, based on the frequency spectrum of the pupil activity (Medeiros et al., 2025). This inference is analogue to Heart Rate Variability analysis, since its bands reflect changes in the autonomic nervous system (ANS). HRV is classically subdivided in three distinct frequency bands: the VLF band (0-0.04 Hz), the LF band (0.04-0.15 Hz) and the HF band (0.15-0.40 Hz). Specifically, LF implies a more dominant sympathetic activity, while HF is more driven by the parasympathetic branch. The low-to-high frequency ratio (LF/HF) is known as an index of sympathovagal balance (Pagani et al., 1997).

There is little consensus regarding the exact definition of frequency bands and the selection of appropriate statistical methods. Most studies have been used the well-established frequency bands of Heart Rate Variability (HRV) (Lee et al., 2004; Sakamoto et al., 2009; Couceiro et al., 2019).

Recently, Medeiros et al. (2025) conducted a study to define optimal frequencies boundaries for assessing cognitive load. In the controlled experiment with programmers inspecting software bugs, they identified two optimal bands by using HRV as a reference framework: the low-frequency band (0.06-0.29 Hz) and the high-frequency band (0.29-0.49 Hz).

In resting state conditions, only a study has been found (Piu et al., 2019). The authors investigated pupil oscillations under stationary scotopic conditions as potential indicators of cortical resting state activity. They focused on low (0-0.15 Hz) and high (0.15-0.45 Hz), believed to drive spontaneous pupil fluctuations. To examine interactions between these oscillators, the study analyzed their phase-space trajectory patterns. The applied empirical mode decomposition to determine the pupil signal frequency spectrum; then they utilized cross-recurrence patterns of trajectories to reveal the non-linear dynamics; finally, global and local recurrence patterns of trajectories were quantified using determinism and entropy parameters. They observed a balanced cholinergic/noradrenergic tone in pupil size oscillations: a 95% prediction ellipse in the entropy-determinism space identified normative values with healthy ANS activity.

In summary, given the shared regulation of heart rate variability and variability in pupil diameter by the autonomic nervous system, pupillography represents a promising tool for assessing psychological states related to arousal and cognitive load. However, further research is essential to fully establish its reliability, especially in resting state conditions.

Summary

This chapter has focused on the resting state EEG and pupillometric techniques that have been employed for this study and their underlying cerebral mechanisms. In particular, more emphasis was placed on frequency bands in electroencephalography, alongside pupil diameter and pupil frequency in pupillometry. Additionally, the characteristic patterns reported in scientific literature for healthy elderly individuals were also presented.

Specifically, studies involving healthy elderly individuals found:

- Contrasting studies in alpha power;
- Smaller delta and theta power compared to younger adults;
- A higher baseline pupil size compared to younger adults;
- A less dynamic resting-state pupil size variability compared to younger adults.

Lastly, the Cognitive Load construct was introduced in relation to power frequency bands and pupil indices. Generally, during periods of heightened arousal, one would expect the following:

- A smaller alpha power;
- A higher theta power;
- A greater pupil dilation;
- A greater pupil size variability.

The CLT framework serves as a basis for the hypotheses of the experimental study that will be delineated in the next chapter.

CHAPTER 3: THE STUDY

3.1. Background data collection: DigitAl lifelong pRevEntion (DARE) project

This study is situated within the DigitAl lifelong pRevEntion (DARE) project. This is a project financed by the MUR in the National Plan for investments (PNRR) with the aim to gather information to define, monitor and promote health trajectories in the entire life course.

At the University of Padova, in particular, the study *Clinical, cognitive and neuropsychological markers of healthy ageing* focused primarily on the elderly population. The longitudinal experimental design involved a first session in which cognitive, physiological and behavioural indices were gathered, and a second session, a year later, to check if they had developed any dementia syndromes. The aim of this study was to find possible bio-markers of dementia syndromes.

Therefore, the data collection for this experiment included various types of instrumentation (see further at paragraph 3.3.2. Procedure).

However, the present thesis focused only on a subset of the collected data: the instrumentation taken in exams comprehended the analysis of resting state EEG and eye-tracking data, and the analysis of the Gudjonsson Suggestibility Scale scores (GSS-2). More specifically, analyses were conducted using the power spectrum density (PSD) of EEG signals as well as pupillary diameter and pupillary frequency.

3.2. An exploratory study: aims and hypotheses

The aim of the study was to find potential cerebral and pupillometric markers of suggestibility. The hypotheses revolved around the fact that brain rhythms and pupil behaviour of highly suggestible individuals would resemble those observed in an aroused and cognitive loaded state, in accordance with the studies conducted in the Cognitive Load framework. Specifically, highly suggestible individuals may exhibit a baseline pupil size and brain rhythms comparable to those expected in states of heightened arousal.

Therefore, four main hypotheses were formulated:

1. High suggestibility is correlated with less alpha activity;
2. High suggestibility is correlated with more theta activity;
3. High suggestibility is associated with a higher baseline pupil size, given the roust link between heightened arousal and pupil dilation;
4. High suggestibility is associated with greater pupil size variability.

3.3. Experimental Settings

The testing of the participants examined in this thesis took place in six months, from the beginning of March 2025 to the end of October 2025.

The study was financially compensated: at the end, the participants received a retribution of 100 euros.

The research was conducted in compliance with the latest privacy regulations, that were written in the informed consent they signed at the beginning of the first experimental session. The participant voluntarily authorized the analysis of their data uniquely for scientific objectives in confidential terms. Indeed, the data collected were processed anonymously and used for statistical analysis purposes, and their access was strictly limited to the researchers involved.

3.3.1. Selection of participants

The participants involved in this research study were recruited on the basis of a non-probabilistic sampling for convenience method.

They needed to comply with various criteria in order to be included:

1. They needed to be at least 64 years old;
2. They needed to know the Italian language;
3. They needed to be healthy individuals: it was necessary not to have a diagnosis of dementia syndromes or any psychiatric disorders.

From the initial 52 participants, the data of $n = 29$ were kept. The participants were excluded for three main reasons (see further paragraph for the specifics of the removal):

1. A score in the Mini Mental State Examination (MMSE) below 25 ($n = 1$);

2. No or incomplete eye-tracking data (n = 8);
3. Poor data quality for both EEG and eye-tracking (n = 14).

The 29 participants that were finally kept (19 females and 9 males) ranged from 64 to 88 years old (mean = 72.41; sd = 6). The level of education broadened from 5 to 22 years (mean = 12.07; sd = 4.44). The scores of the MMSE ranged from 25 to 30 (mean = 28.76; sd = 1.27). The big majority of the participants were right-handed (n = 26), while only one of them was left-handed and n = 2 were corrected left-handed.

3.3.2. Procedure

The participants were tested in two separate days, categorized as "T1" and "T2". Each session lasted nearly 2.5 hours each.

In T1 the participants were tested with the gait analysis and the neuropsychological assessment.

Specifically in chronological order:

- The immediate memory recall of the *Gudjonsson Suggestibility Scale (GSS-2*, Gudjonsson & Clark, 1986) (as described above in Paragraph 1.2.3. A scale to assess suggestibility: The Gudjonsson Suggestibility Scale (GSS-2));
- The *Gait analysis* (protocol Helen Hayes MM), in which the participants were asked to execute two standing tasks (one with the eyes open and one with the eyes closed) and 8 walking tasks;
- *CRI-Q* (Nucci et al, 2012), to evaluate the cognitive reserve;
- The delayed memory recall of the *Gudjonsson Suggestibility Scale (GSS-2*, Gudjonsson & Clark, 1986), after a retention of 50 minutes of non-confounding tasks;
- *Mini Mental State Examination (MMSE)* (Magni et al, 1996);
- *Digit span* (forward and backward) (Monaco et al, 2013);
- *PASAT* (Saetti, 2021);
- *Prose memory* (immediate recall) (Mondini et al, 2011);
- *Figure of Rey* (immediate recall) (Caffarra et al, 2002);
- *Prose memory* (delayed recall) (Mondini et al, 2011);
- *Figure of Rey* (delayed recall) (Caffarra et al, 2002);

- *15 words of Rey* (immediate recall) (Carlesimo et al, 1996);
- *Trail Making Test (TMT*, part A and B) (Mondini et al, 2011);
- *Clock drawing test* (Mondini et al, 2011);
- *Attentional matrices* (Spinnler & Tognoni, 1987);
- *15 words of Rey* (delayed) (Carlesimo et al, 1996);
- *Stroop test* (Caffarra et al, 2002);
- *Phonemic fluency* (Mondini et al, 2011);
- *Abstraction test* (Mondini et al, 2011).

After that, the participants completed various questionnaires:

- The *Depression Anxiety Scales Short Version (DASS-21)* (Henry & Crawford, 2005) to evaluate the levels of anxious, depressive and stressed state;
- The *Pittsburgh Sleep Quality Index (PSQI)* (Smyth, 1999) to evaluate the sleep quality;
- The *Satisfaction Life Scale (SWLS)* to evaluate the well-being quality of life (Diener et al, 1985);
- The *Eating Disorders Questionnaire* to evaluate the eating habits;
- A questionnaire (University of Bologna, DARE) to evaluate motor abilities and the fall frequency.

In T2, participants were administered the *Montreal Cognitive Assessment (MoCA)* (Pirani et al, 2006).

After that, they were required to do computerized tasks, designed and implemented using the OpenSesame software (Mathôt et al., 2012), with the recording of EEG and eye-tracking instrumentations.

Precisely, in chronological order:

1. *Resting state with the eyes open* (5 minutes). The participant was requested to stay as still and relaxed as possible and to look at the blank grey screen of the computer without any stimulation. No central fixation cross was provided.
2. *Free viewing* (20 minutes). The participant was asked to look at some images, sourced from the database *Places365* (Zhou et al., 2017).
3. *Visual search* (40 minutes). The participant was asked to look at the same images presented in the Free viewing task. However, in this task he needed to press the

space bar anytime he saw a grey small circle placed in a different point on the screen each image.

In between these three tasks, the participant was permitted to take a brief break.

There was a period of one week between T1 and T2. In between these days, participants were required to wear an actigraph, in order to obtain physiological indices and motor activity.

N of them did T1 first, while n of them were firstly tested with the instrumentation described above in T2.

The procedure described is the standard protocol adopted for the complete study (*Clinical, cognitive and neuropsychological markers of healthy ageing).*

However, as mentioned above, the present thesis focused on the results of the Gudjonsson Suggestibility Scale (GSS-2) and the analysis of the resting state hd-EEG and the pupillometric data derived from the eye-tracker (see further paragraph 3.3.3. HD-EEG and eye-tracking setup).

3.3.3. Administration of the GSS-2: the setting

The Italian version of the Gudjonsson Suggestibility Scale (GSS-2) (Curci & Bianco, 1997, 2016) was administered as the first test before the gait analysis.

The immediate and delayed recall was recorded, prior consent of the participant, in order to have a more reliable source for the scoring of Immediate recall, Delayed recall and the indices of Distorsions, Inventions, Confabulations and overall Total suggestibility score. (see the previous paragraph 1.2.3. A scale to assess suggestibility: The Gudjonsson Suggestibility Scale (GSS-2)).

The GSS-2 was administered in the room where the gait analysis took place. The setting consisted of a big mat situated at the centre of the room. Around the mat there were placed eight cameras that detected the markers placed in the participant body for the gait analysis. Immediately adjacent to the mat there were two desks: one had the computer that managed the cameras and therefore the gait analysis, while the other one was designated for the neuropsychological assessment and the administration of the GSS-2.

Figure 7. *The setting for the administration of the GSS-2. The participant sat on the chair on the left, while the experimenter was positioned in front.*

3.3.4. HD-EEG and eye-tracking setup

Previously, the participant was alerted not to wear any makeup, nor any recent hair color. Firstly, if it was the case, the participant was asked to remove the earrings that could have damaged the plastic nets of the HD-EEG cap.

The participant was conducted in a temperature-controlled room: the radiators during cold days and the air conditioning system during the summer ensured a relatively stable temperature. In particular, when the participant was tested during hot days in summer, the combination of the air conditioning system and allowing the participant sufficient time to recover the temperature were precious measures.

The setting consisted of:

- A desk intended for the administration of the *MOntreal Cognitive Assessment (MOCA)* (Pirani et al, 2006), that took place prior to the HD-EEG setup;
- A desk with the monitor (pixels) that presented the stimuli and in which the physiological measures of eye-tracking and EEG were recorded;
- An adjustable-height chair to position the eyes at the appropriate level, enabling the eye-tracker to detect the pupil and corneal reflexes of both eyes;
- Two cameras oriented towards the two desks, enabling the experimenter to closely observe the participant, detect potential movements and record them in the participant form.

Efforts were made to maintain a consistent luminance level. However, some light filtered through the curtains, which constitute a limitation to the study, as data collection took place throughout the entire year, with the consequently variations in lighting conditions. Indeed, this could interfere in the pupil dilation, as the pupil is sensitive to light.

Figure 8. *These photos were taken from the experimental setup (a lateral view on the left and a frontal view on the right). The sequence includes the adjustable chair, the chin-rest, the keyboard, the tripod equipped with the eye-tracking device and the monitor presenting the experimental conditions. On the side, the amplifier to which the hd-EEG is connected, is placed on a trolley.*

The experimenter room consisted of two desktop computers: the PC stimuli strictly related to the eye-tracker and the PC that connected with the amplifier of the HD-EEG. Prior to the connection of the eye-tracker in the participant's room, the laptop of the eye-tracker was utilized for the calibration, validation and successively the recording of the tasks.

The mixer permitted the switching between the computers, allowing the displays of the cameras oriented towards the participants and other computers to be projected onto larger monitors.

Figure 9. *Shown in the photo are the monitors located in the experimenter's room: the stimuli presentation PC, the EEG system, the eye-tracker device interface and the feeds from two cameras used to monitor the participant.*

3.3.4.1. HD-EEG recording

3.3.4.1.1. The Standard 128Ch actiCAP snap

The high-density EEG (HD-EEG) cap used in this study was the Standard EEG actiCAP snap with 128 active electrodes (ActiCHamp Plus amplifier). The positions of the holders derived from the 5% and the 10% Systems. The electrodes were subdivided into four bundles in different colours assigned to four different amplifier channels, while the ground (GND) electrode was plugged into the black holder (Fpz). The hardware used (actiCHamp) did not have the reference electrode (NO REF), thereby the electrode 32 from 2nd bundle (yellow colour) was used to record from FCz.

The gel electrode used for this specific HD-EEG was the SuperVisc HighViscosity Electrolyte-Gel for active electrodes, a water soluble and a high-viscosity gel with high salt concentration, allowing the EEG setup to achieve its optimal impedance faster.

3.3.4.1.3. HD-EEG setup

At first, the HD-EEG cap was placed on the participant's head prior to taking the head measurements. Two different caps were used depending on the circumference of the head:

the cap of 56 cm, usually used for female participants, or the cap of 58 cm, usually used for male subjects.

Afterwards, the cap was adjusted to be in the right centre of the head. With a simple meter the distance between nasion and inion and the distance between the tragus of the ears were taken.

Once the cap was adjusted into the participant's head, the SuperVisc gel was injected using metal blunted needle syringes into the cap under each of the 128 active electrodes, in order to keep the impedance low.

After that, the amplifier was connected to reveal the level of impedance of each electrode: Since they are active, at this point the colour of the electrode indicates the level of impedance and contact with the skin: we tried to have every electrode green, but sometimes it was not possible due to the high impedance of the skin.

After the montage of the EEG cap, the chair was adjusted, in order to maintain an adequate height for the eye-tracker to capture the corneal reflex and the pupil diameter of the eyes. Finally, the HD-EEG setup was completed, and the eye-tracker could be prepared.

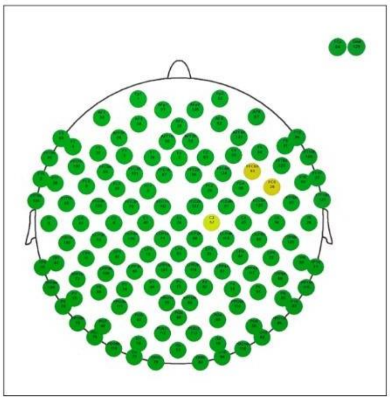


Figure 10. *The figure displays a successful impedance check of a participant of this study. The separated dots on the top right are respectively the Fcz (64) and the Ground electrode (129).*

3.3.4.2. Eye-tracking recording

3.3.4.2.1. The EyeLink Portable Duo

The eye-tracker data were recorded via the EyeLink Portable Duo (Version 6.50 SR Research), an eye-tracker intended for the most sophisticated eye-movement research, both in and out the laboratory environment.

By enabling accurate data, due to the consistent binocular sampling rate, up to 2000 Hz, the Portable Duo delivered high-precision, sample-level data, alongside accurate and reliable measurements of gaze position, microsaccades and pupillometry.
The reliability of this video based eye tracking derived by the combination of the near-infrared video camera and the near-infrared light-emitting diodes (LEDs) that illuminated the eye (Papesh & Goldinger, 2024). The pupil appeared as the darkest part of the camera's image, whereas the reflection of the cornea corresponded to the brightest part. Complex image processing algorithms identified the centre of landmarks such as the pupil and corneal reflection. Following the calibration procedure (see further paragraph 3.3.3.2.3. The calibration), the vector between the center of the pupil and the center of the corneal reflections was used to calculate the gaze position. Pupil size was also measured, by calculating the number of pixels below a defined brightness threshold, considered part of the pupil (Papesh & Goldinger, 2024).
The reliability of the EyeLink Portable Duo was also seen in the compensation for head movements. In order to compensate for head movements that would have made ambiguity on distinguishing pupil position changes caused by eye rotations from those caused by head shifts, this eye-tracking system exploited the different behavior of the pupil-to-corneal reflection (Pupil-CR) relationship. Indeed, during head movements, the relationship between the center of the pupil and the center of the corneal reflection remained the same, whereas it varied when the eye rotated. In "Pupil-CR" tracking, the change in CR position was "subtracted" from the displacement of the pupil, thus enabling the system to disambiguate genuine eye rotations from shifts in pupil position due to head movement.
The EyeLink Portable Duo did not capture facial identifiable data of the participants' faces, in compliance with the privacy policy.

3.3.4.2.2. The Eye-tracker setup

The eye-tracker was mounted on a tripod under the display monitor that the participants were instructed to look at.
The EyeLink was configured in such a way as to:

- The distance between the back of the camera and the display monitor was 530 mm;
- The distance from the eyes to the top of the viewable portion of the display PC was 1050 mm;
- The distance from the eyes to the bottom of the viewable portion of the display PC was 1070 mm;
- The default display resolution was set to 1920 (width) x 1080 (height) pixels, while the viewable portion of the display PC was 600 (width) x 340 (height) mm.

In addition, a chinrest was used in order to have the head stabilized in the horizontal centre of the monitor.

At first, the camera setup was needed. Therefore, the focus of the Eyelink camera was adjusted and the participant was positioned in such a way that the camera captured both the eyes at the same distance from the exact centre.

Successively, a tracking status panel indicated the position of the participant's eyes within the tracking box. Owing to its tracking box, the pupil and corneal thresholds were adjusted manually and more precisely.

Specifically, the thresholds were determined as follows:

- *Pupil threshold.* A pupil was determined as properly thresholded only if it was solidly blue. If the threshold was too low, the blue area was configured as smaller than the pupil, otherwise, there would be shadows at the edges and corners of the eye.
- *Corneal reflex threshold.* To properly adjust the CR threshold, two main outcomes were encountered: the loss of the CR and the CR smearing. In the first case, a "PUPIL MISSING" or "CR MISSING" error message was displayed. Therefore, it was necessary to ask the participant to slowly look along the edges of the display surface and ensure that the corneal reflection does not get lost. The second case, on the other hand, usually indicated that the viewing angle was too large for the setup. Raising the eye tracker camera helped to maintain the correct CR threshold.

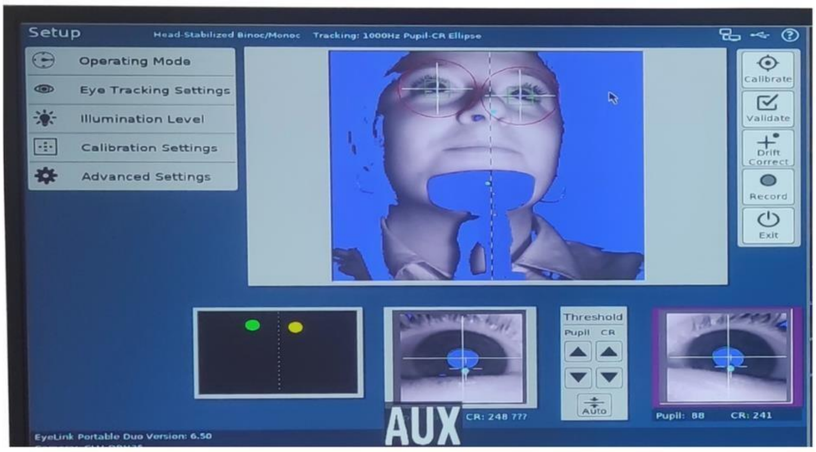


Figure 11. *The image shows the initial setup interface of the eye-tracker, from which the threshold parameters can be adjusted before beginning the calibration process.*

3.3.4.2.3. The calibration and the validation

Once the setup was complete, the calibration took place with validation following afterwards.

The calibration consisted in collecting gaze position samples when targets were being presented. The aim of the calibration procedure was to provide a mapping function that allows raw eye tracking data to be converted to screen co-ordinates. In this study the calibration type consisted of 13-points to get the best recording accuracy, particularly at the corners of the screen.

The participant was instructed to fixate the centre of each target that appeared in the monitor, while samples were collected by the PC in the experimenter room. The auto-mode was rejected, preferring the manual mode for accepting the fixations in the best way possible.

Feedback messages about the quality of the calibration were provided: the calibration was accepted solely when it was indicated as “good”. If this criterion was not met, the calibration procedure was repeated. Indeed, dedicating time to a proper calibration permitted reliable measurements of the ocular data.

To increase data quality, the participant was encouraged to keep close attention and precisely fixate each target without looking away. By providing clear and detailed instructions, the participant's motivation was carefully considered.

For completeness, it was noted if the participant wore glasses, or if he had any visual disturbances or any eye operations done.

Indeed, the eye-tracker faced various problems that have interfered with the data quality (Klein & Ettinger, 2019). Specifically, some of them are further described, alongside with the solutions that have been implemented during the data collection:

1. *Makeup.* The use of make-up, in particular black mascara or fake eyelashes could have interfered with the image processing algorithms that locate the pupil's edge, due to the dark colour that could have resembled the pupil's color (Klein & Ettinger, 2019).
   This was the main reason why the participant was asked to not wear any eye-makeup.
2. *Contact lenses.* Hard contact lenses tended to float, causing a distortion of the shape of the pupil and consequently confusing the algorithms that calculated the pupil's centre (Klein & Ettinger, 2019).
   Indeed, the participant was asked to use glasses instead of contact lenses.
3. *Glasses.* However, also the glasses could have created artifacts. Especially glasses with thick or dirty lenses, by obscuring the view of the eye from the camera and scattering infrared light, distorted the algorithms that were used to illuminate the eye and provide the corneal reflection (Klein & Ettinger, 2019).
   If it was the case, the lenses were cleaned and if the problem persisted, repositioning the participant's head would move the reflection out of the way.
4. *Ptosis.* Droopy eyelids could have occurred with tired or drowsy participants, particularly in elderly individuals. By obscuring the top of the pupil, the top eyelid interfered with the image processing algorithms that determine its centre. (Klein & Ettinger, 2019).
   Under these circumstances, repositioning the camera and having a steeper angle helped.

After the calibration was completed, the validation was required.
The validation procedure showed the experimenter the gaze position accuracy achieved by the current calibration model. At the end, feedback messages similar to the calibration results were shown (see the previous table.) In this case, each eye was graded separately.

If a large error happened at only one specific target, it indicated the participant's gaze was inaccurately focused at that specific point, necessitating a repeat of both the validation and the preceding calibration.

The aim was to measure a binocular recording for all the participants. However, It happened that for the majority of the participants (n = 19) an accurate validation was not possible for both the eyes. In these cases, the recording was monocular.

Upon the successful completion of the calibration and validation processes, pressing the "Record" button initiated the recording of the EEG and eye-tracking signals.

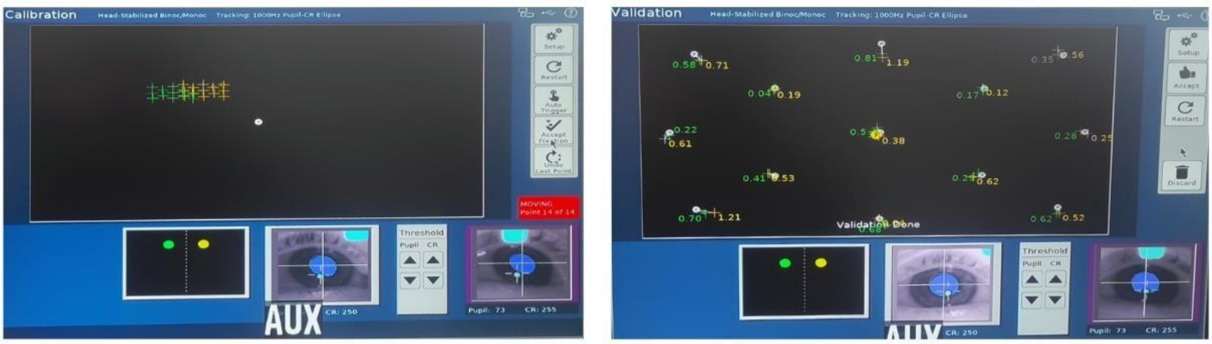


Figure 12. *An example of a successful calibration (on the left) and validation (on the right).*

3.5. Analysis of resting state EEG and pupillometry

For both EEG and pupillometric measures the preprocessing procedure was needed to improve the quality of data before further analysis and interpretation. Thereby, the distinctive steps are described.

3.5.1. Preprocessing of resting state EEG data

The Resting state EEG data analysis was conducted in MATLAB. Specifically, the toolbox EEGLAB, a graphic user interface and an interactive environment for processing EEG data, was used (Delorme & Makeig, 2004).

The main aim of the preprocessing was to obtain a spectral analysis of the resting-state EEG signal. Thereby, the data analysis was conducted based on the processing pipeline (), as described hereafter:

1. *Re-referencing to FCz.* At first, FCz was set as the common reference channel for all electrodes:
2. *Extracting the resting-state segment.* The signal segment between event markers of start (S1) and end (S2) was selected.
3. *Band-bass filtering.* A high-pass filter was set at 1 Hz to remove slow drifts, combined with a low-pass filter at 45 Hz to remove high-frequency noise.
4. *Downsampling.* The sampling rate was reduced to 250 Hz.
5. *Removing bad channels.* Channels that were flat longer than 5 seconds, had poor correlation with the reconstruction from neighbouring channels (<0.8) and contained excessive line noise or showed abnormal amplitude variance were automatically removed. In some cases, manual removal of other problematic channels was also needed.
6. *Interpolation of bad channels.* Spherical spline interpolation permitted the reconstruction of the removed channels.
7. *Re-referencing to average.* EEG signals were re-referenced to the average of all channels.
8. *Independent Component Analysis (ICA).* At first, through IClabel classification ('brain', 'muscle', 'eye', 'heart', 'line noise', 'channel noise', 'other'), only 'brain' and 'other' components were kept.
9. *Computing of Power Spectral Density (PSD).* The PSD provided an estimate of spectral power distribution for each frequency (range from 1 to 40 Hz). The values were normalized, by dividing each spectrum by mean value, and subsequently relative and absolute spectra were converted into tables for a further analysis.
10. *Exporting of individual topoplots by frequency range and band name*. Alpha (8-13 Hz), Beta (13-30 Hz), Delta (1-4 Hz), Theta (4-8 Hz) bands were displayed, alongside the generation of the topographies.

In between these passages, the EEG signal was often plotted in order to have a check of the signal, as the following figures show.

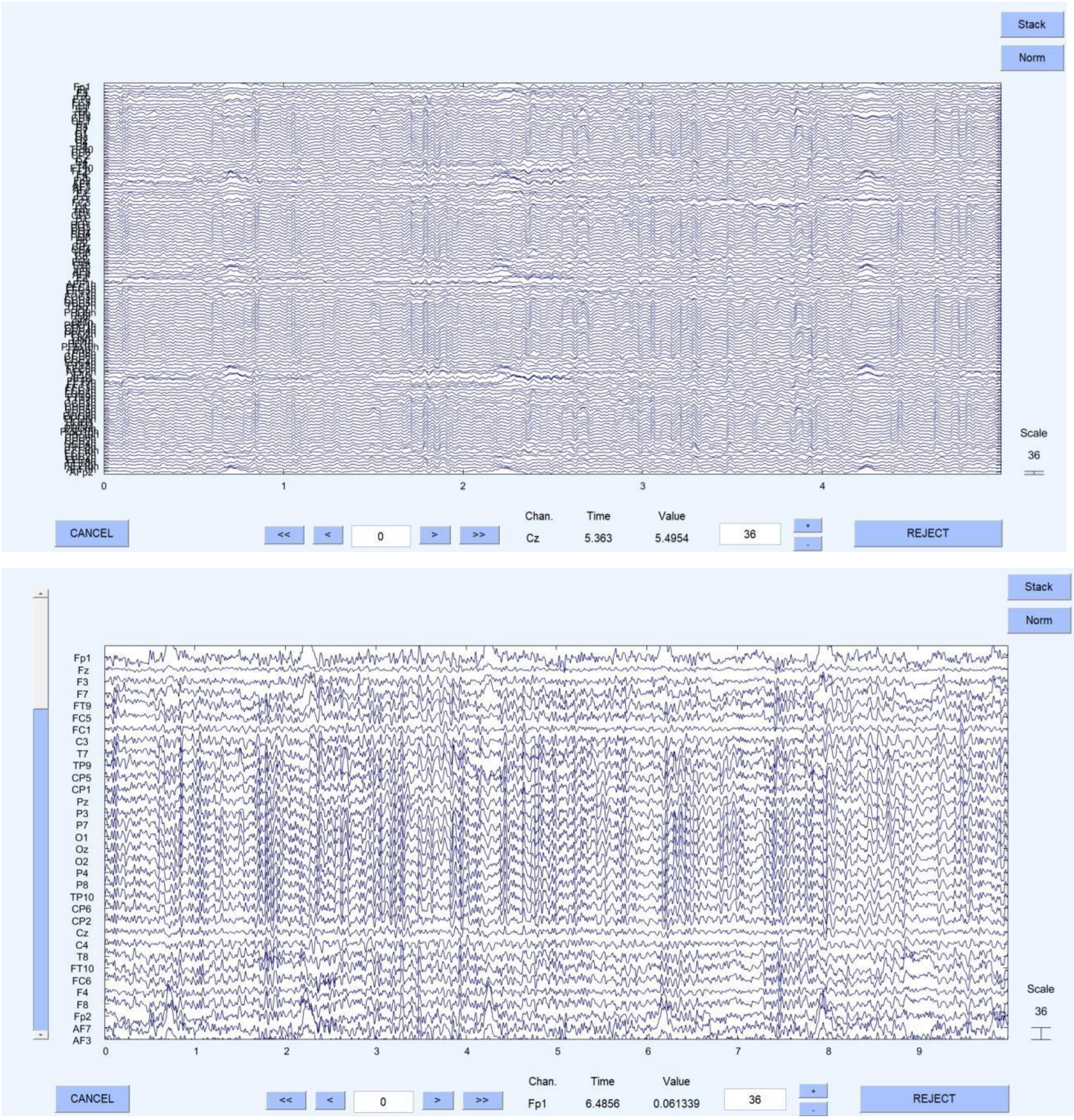


Figure 13. *Examples of channel scrolls. The figure at the top displays an overview of all channels in a time range of 5 seconds. The figure at the bottom shows a zoom-in of 32 channels in a time range of 10 seconds.*

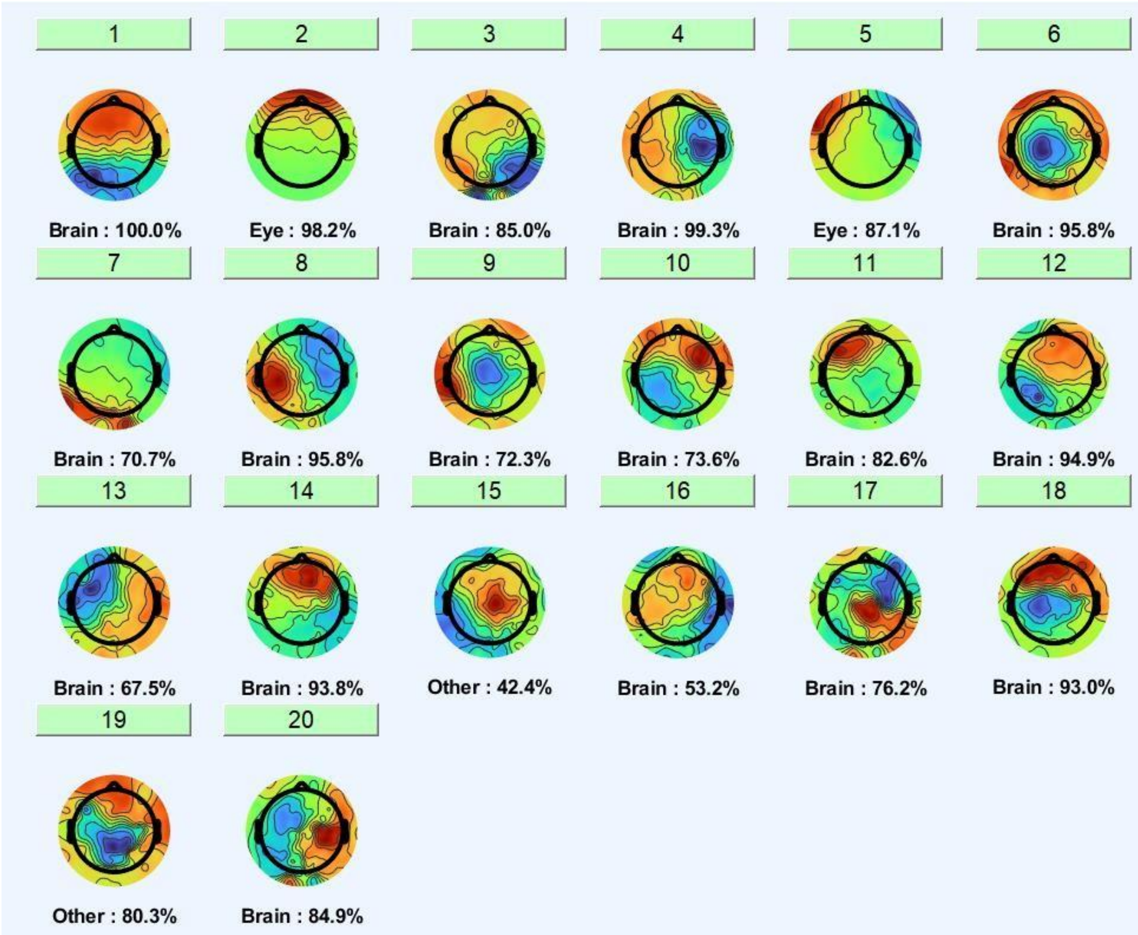


Figure 14. *Overview of an ICA inspection. The first 20 components are here labeled (IClabel).*

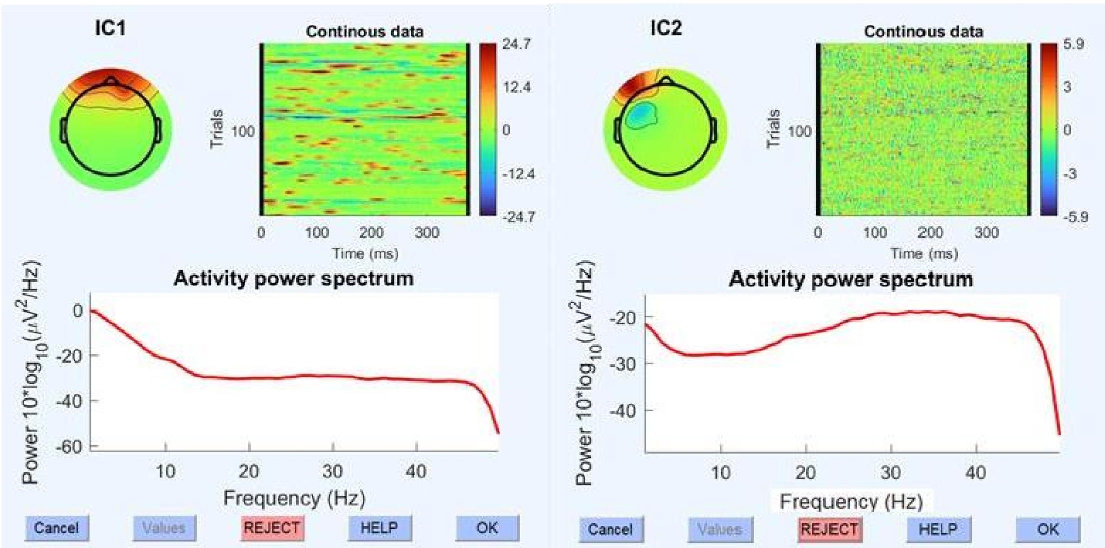


Figure 15. *Examples of two rejected IC. On the left (IC1), an example of eye movements artifact. On the right (IC2), an example of a muscle artifact.*

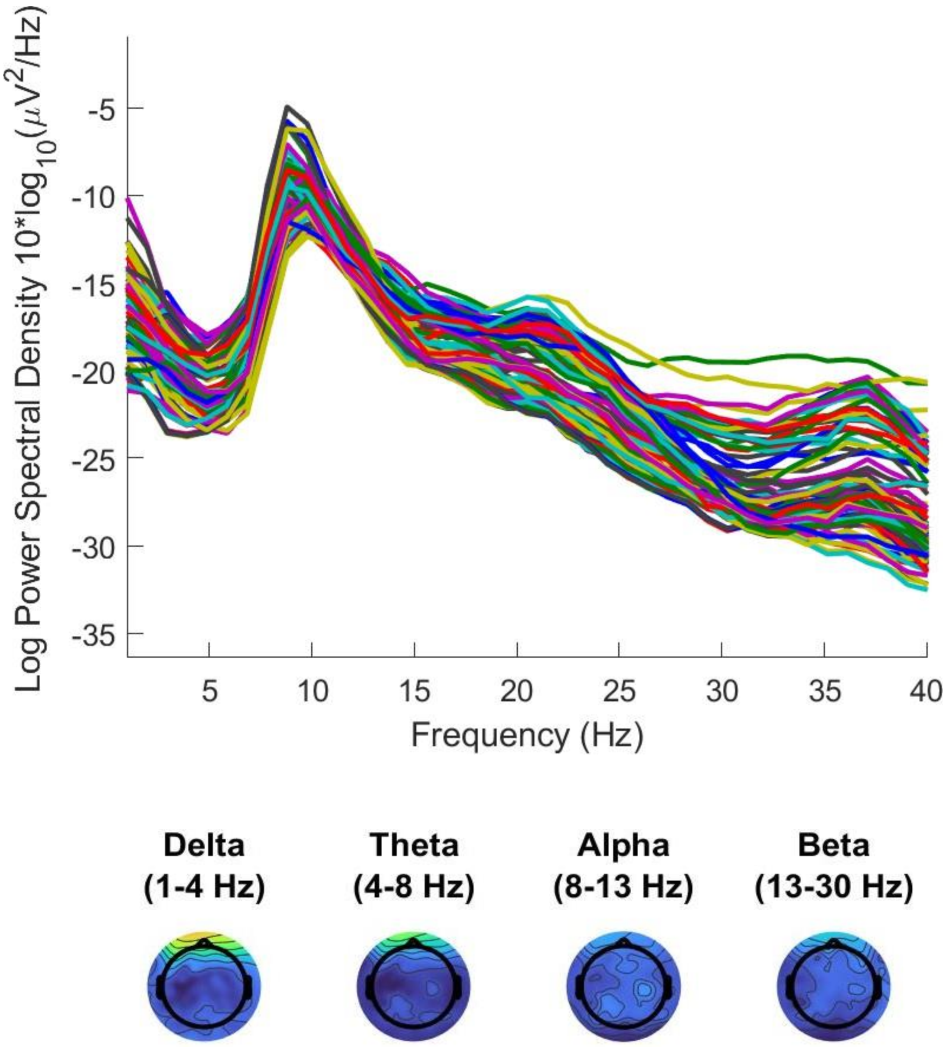


Figure 16. *Examples of a subject's power spectrum (at the top) and topographical map (at the bottom).*

3.5.2. Preprocessing of resting state pupillometric data

From 9 participants, the recording of both the eyes was completed. The other subjects were monocularly recorded (n = 4 for the right eye; n = 16 for the left eye).

The majority of the excluded participants, indeed, were removed mainly due to problems related to a struggle of the eye-tracker to track the eyes. Indeed, several participants suffered from cataract or ptosis as a consequence of the elderly age, which altered the eye-tracker algorithm in detecting the CR and pupil thresholds.

The Resting state pupillometric data analysis was conducted in Rstudio. The preprocessing was carried out in accordance with the pipeline described by Mathot et al (2022) and Kret et al (2018).

1. *Parsing raw data.* A conversion from the raw (.edf) eye-tracking file to ASCII was needed in order to create an analyzable dataframe into R. The time duration of the analyzed signal was kept at 70 sec and not any longer: going up with the time course, the signal began to deteriorate, probably because of the age of the subjects.
2. *Handling missing data.* Subjects who had more than 50% of missing pupillometric data were removed from the analysis.

Figure 17. *This graph displays the missing data of the subjects. In this case, only one subject exceeded the threshold (ID 51).*

3. *Blinks detection.* A filtering pipeline was applied in order to identify and remove invalid pupil size samples (NA values) derived from artifacts such as system errors or blinks. Therefore, disproportionately large absolute pupil size changes relative to their neighbours (*dilation speed outliers*) were identified. Specifically, by using the median absolute deviation (MAD), scaled by a constant, samples with dilation speed above the thresholds (500 ms) were rejected.

After removing the outliers by speed, samples near data gaps were rejected. Those intervals were expanded by 50 ms before (blink onset) and after (blink offset) each blink to ensure a full coverage.

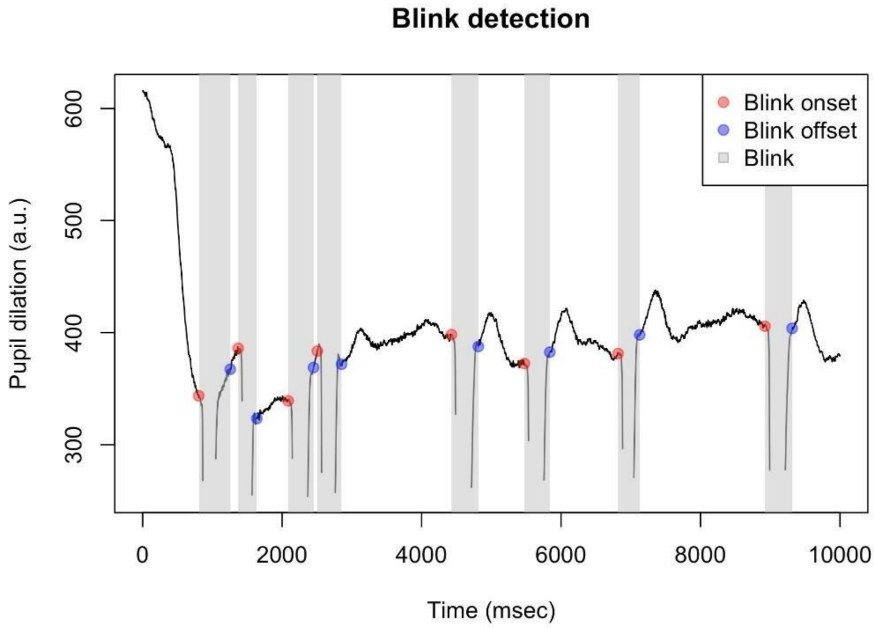


Figure 18. *The figure shows a blink detection, characterized by the blink onsets and offsets marks.*

4. *Calculating mean pupil size (a.u.).* When recorded binocularly, a 'third' mean pupil size measure was obtained by averaging left and right pupil sizes. At this point, the plot displayed a pupil signal characterized by some gaps where data have been removed.
5. *Blinks interpolation.* When data from one pupil was missing, a dynamic offset between pupils was computed at epochs where both pupils were recorded. Subsequently, data were interpolated in order to replace NA values and to derive the mean pupil size.

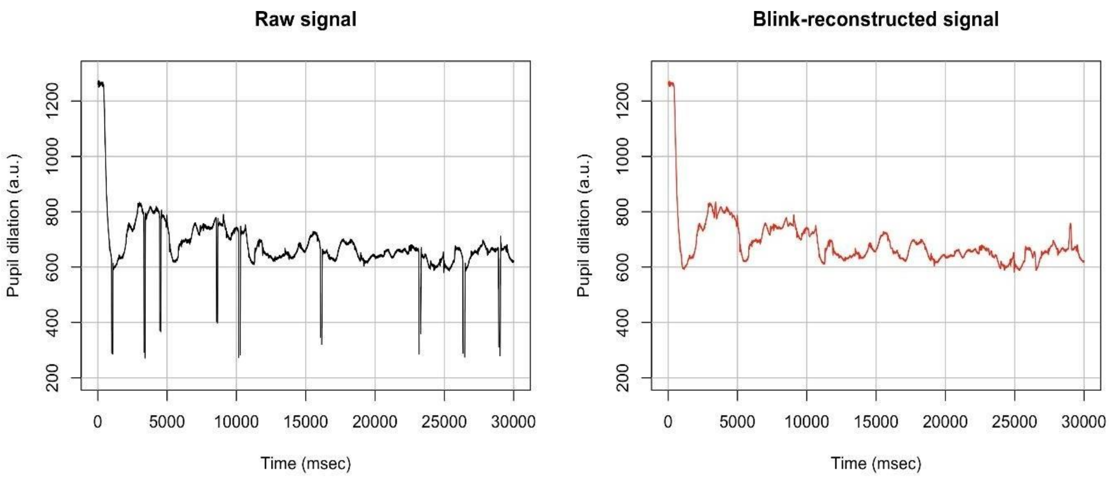


Figure 19. *The plots display the raw signal displaying visible blinks (on the left); the blink-reconstructed signal (on the right).*

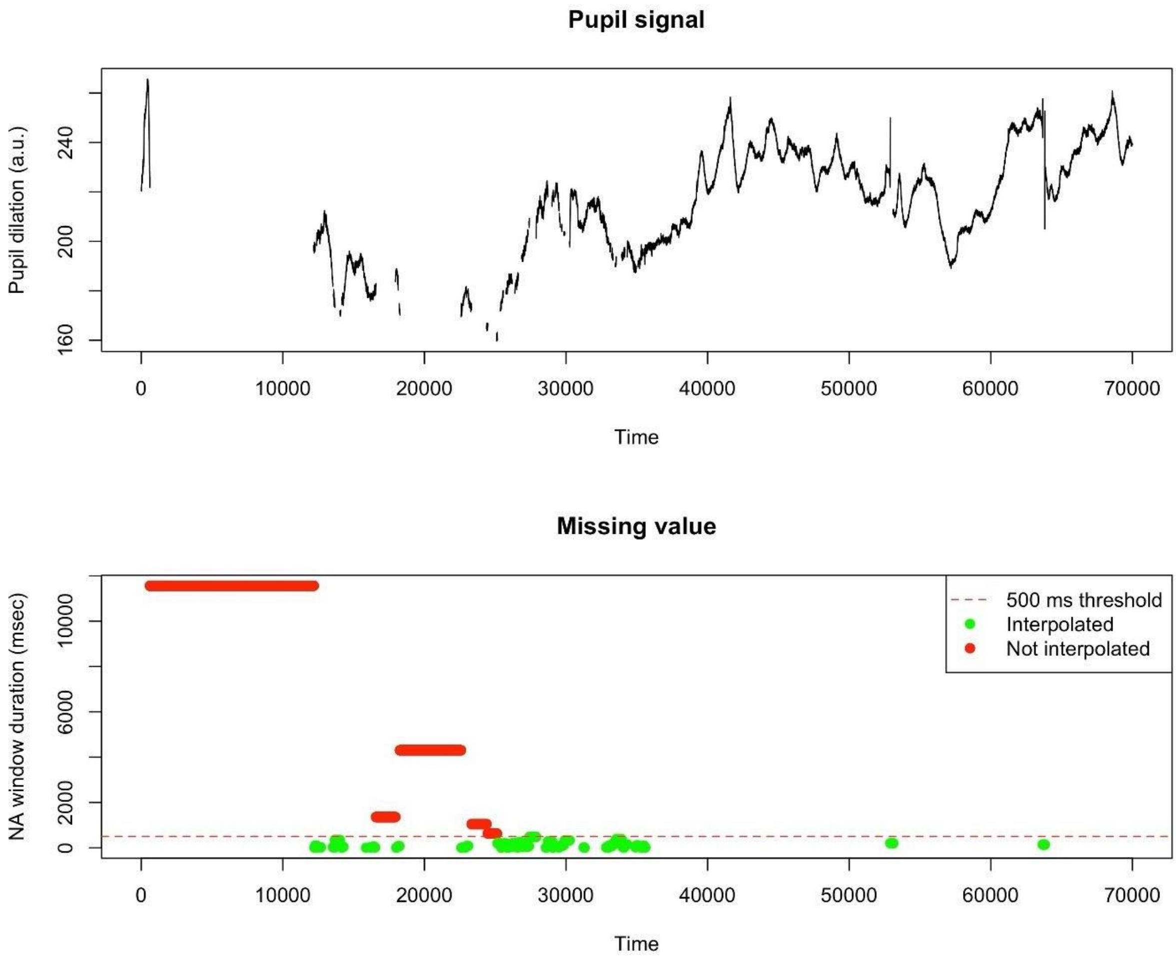


Figure 20. *Example of a plot displaying the pupil signal (at the top) and of a graph showing the missing values (dilation speed outliers) (at the bottom). The threshold was allocated at 500 ms:*

the NA values that fell below this threshold were interpolated (green dots), while the values that lasted longer were not (red dots).

6. *Smoothing.* The signal was smoothed using a zero-phase low-pass filter set at 4 Hz, in order to have a more linear resulting signal.

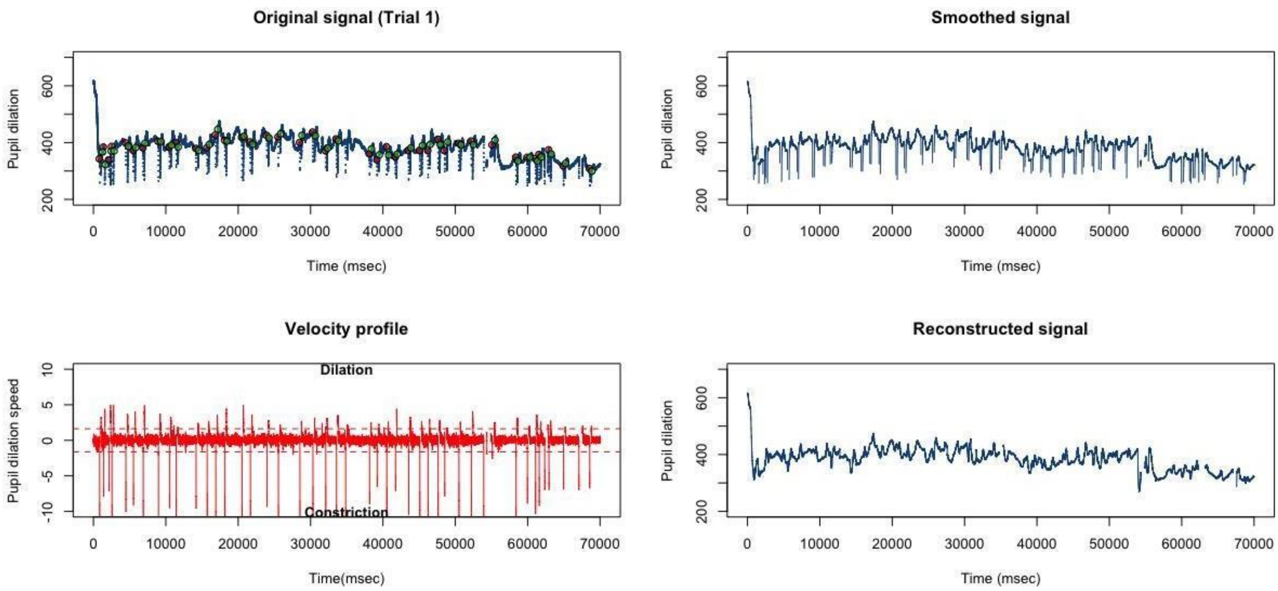
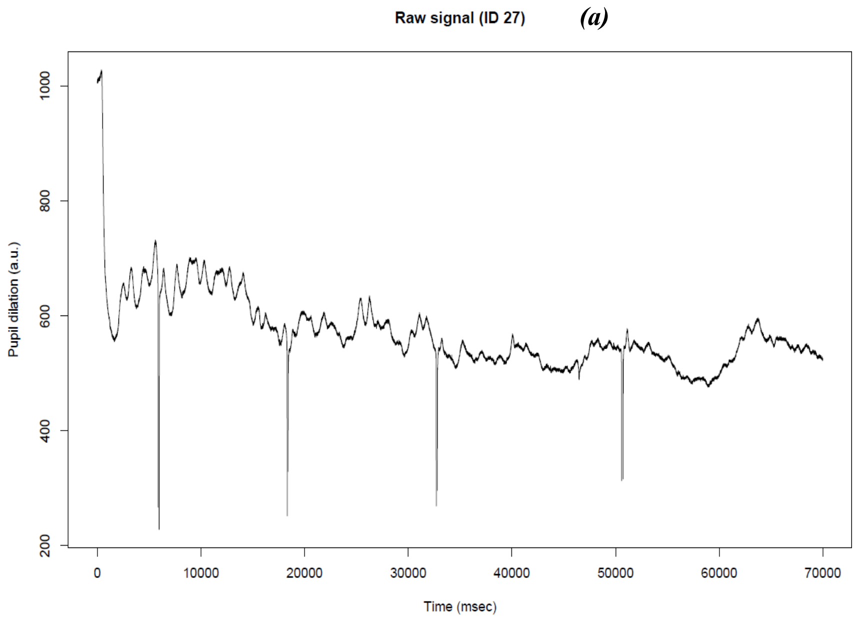


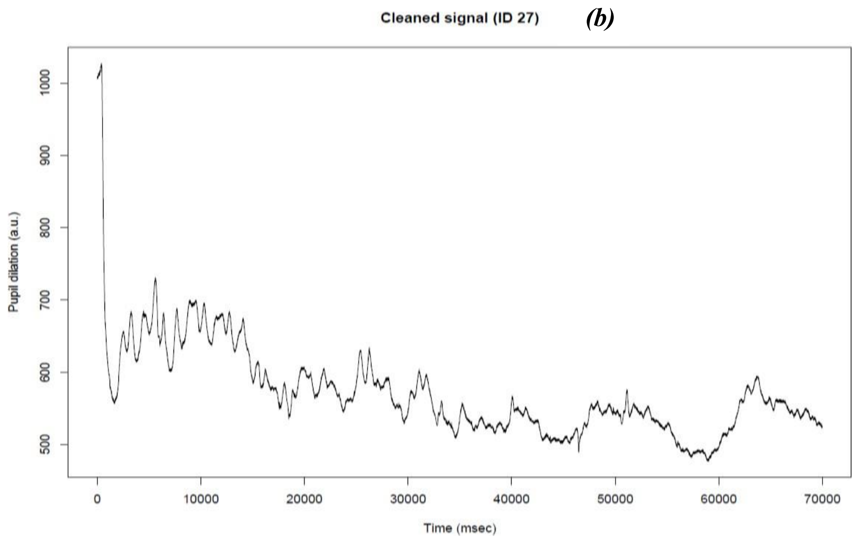
Figure 21. *The plots show the aforementioned cleaning steps. Specifically, the raw original signal, marked by the blink onsets and offsets (a); the smoothed signal (b); the velocity profile of blinks; the final reconstructed signal (d).*

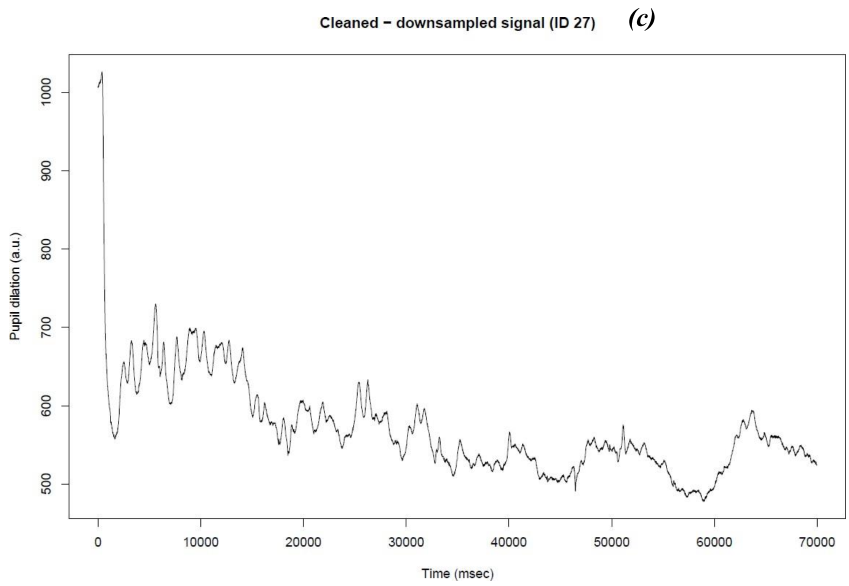
7. *Time zeroing.* Subtraction of the first timestamps permitted the recording to start at zero milliseconds.
8. *Downsampling.* The original sampling rate of 1000 Hz was reduced to 100 Hz. The continuous pupil size signal was segmented into non-overlapping time bins of 50 ms. A smoother representation, alongside a significant reduction of data size, was thereby provided with the calculation of the downsampled mean pupil size.
9. *Baseline correction.* The first 100 ms were used to compute a baseline pupil size mean. This baseline value was consequently subtracted from the time course of the pupil size to correct for initial pupil size offset.

10. *Removing the first 10 seconds*. At this point, the time course displayed was 60 seconds.
11. *Plotting raw, interpolated, downsampled and baseline-corrected data.* Four plots were produced: the first one presenting the unprocessed pupil size data; the second plot showing the interpolated signal; the third one displaying the downsampled and summary signal; the final plot showing the summary signal for the first 60 seconds. Indeed, in order to preserve more physiological pupil dynamics, the analysis was conducted on the first minute: longer periods of inactive wakefulness elicit low-frequency pupil diameter oscillations (*Hippus*) (Montefusco et al., 2022).

For each of the described steps, a visual check of the signal was done, as the following plots display.







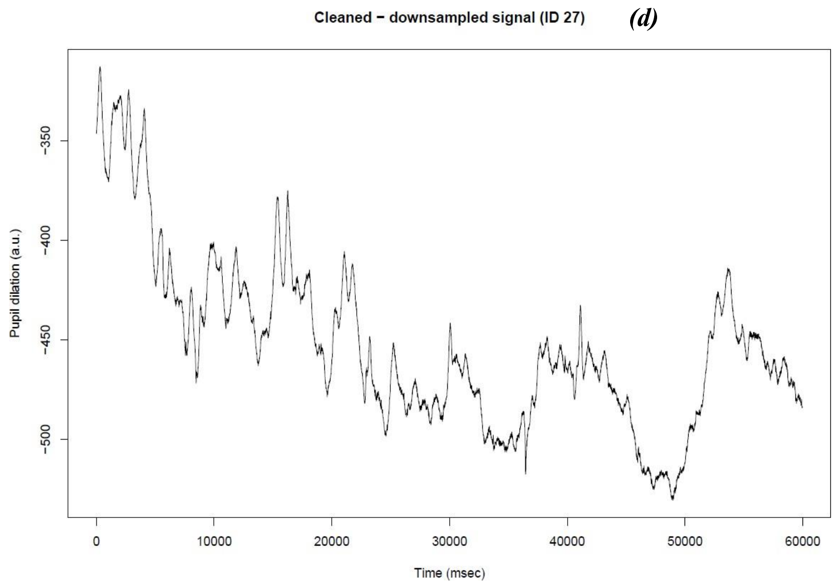


Figure 22. *Examples of the aforementioned preprocessing steps for the subject ID 27. Each plot presents on the x-axis the time course (msec) and on the y-axis the pupil dilation (a.u,). Specifically, the first visual check of the raw and unpreprocessed pupil diameter across time (a); the cleaned pupil diameter across time (b); the cleaned and downsampled pupil diameter across time (c); the cleaned, downsampled and baseline corrected pupil diameter across time for the first minute, with the removal of the first milliseconds (d).*

3.6. Analysis of the Gudjonsson Suggestibility Scale (GSS-2)

The results obtained by the administration of the Gudjonsson Suggestibility Scale (GSS-2) were analyzed using the RStudio integrated development environment (IDE).

Descriptive statistics were conducted among all the indices, as highlighted in the following table. The bold indices (Total Suggestibility, Yield 1, Shift and Yield 2) were further utilized to subdivide the sample of participants.

Indices	*Range*	*Median*	*Mean*	*Sd*
Immediate Recall (IR)	5.5-27	14.5	14.74	5.80
Distorsions (D1)	0-6	2	2	1.49
Inventions (I1)	0-2	0	0.38	0.62
Confabulation (CT1)	0-7	2	2.38	1.70
Delayed Recall (DR)	6-24	14	14.59	5.72
Distorsions (D2)	0-5	2	1.93	1.36
Inventions (I2)	0-2	0	0.59	0.78
Confabulation (CT2)	0-6	2	2.52	1.60
Yield 1	**0-11**	**4**	**3.69**	**2.19**
Yield 2	**1-12**	**5**	**5.17**	**2.98**
Shift	**0-8**	**4**	**3.31**	**2.12**
Total Suggestibility	**1-16**	**7**	**7**	**3.44**

Accounting suggestibility as a continuous trait in individuals (see chapter 1), the statistical analysis was conducted with reference to the study sample, rather than the normative sample. Specifically, the sample was subdivided considering the specific median of the *Total Suggestibility* score of the sample (median = 6.5). Therefore, participants displaying low suggestibility (n = 14) and participants characterized by high suggestibility (n = 15) were confronted. A similar procedure was conducted regarding the Yields and Shift scores. In *Yield 1* index n = 12 participants exhibited scores below the median (median =

4), while n = 17 were at or above. Regarding *Shift* index n = 14 subjects scored below the median (median = 5), while n = 15 exhibited scores equal or above. In *Yield 2* index n = 11 participants positioned below the median (median = 4), whereas n = 18 were at or above the median threshold.

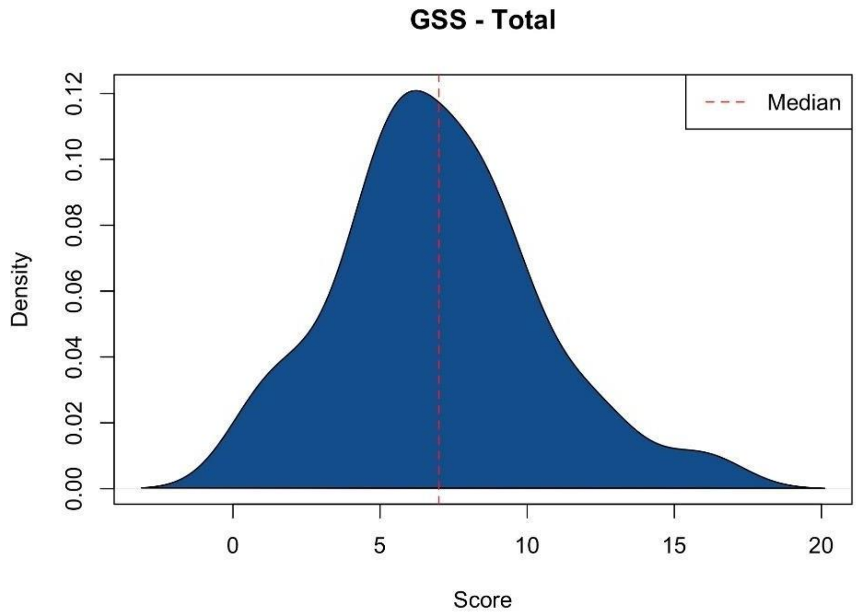


Figure 23. *The graph displays the density distribution of Total Suggestibility scores among all subjects. The median (median = 6.5) subdivided the sample into two groups: the group with low suggestibility scores (< 6.5, n = 14) and the group with high suggestibility scores (≥ 6.5, n = 15).*

3.7. Statistical analysis

As described above, two groups were confronted, by taking into consideration the Total Suggestibility score: the group characterized by low suggestibility, or the *Low GSS* (score < 6.5, n = 14) and the group with high suggestibility, or the *High GSS* (score ≥ 6.5, n = 15). For the EEG power spectra analysis, also the Yields and Shift scores were taken into consideration.

3.7.1. GSS and EEG frequency bands

Linear regression analyses were performed separately for each dependent variable: Total suggestibility, Yield 1, Shift and Yield 2. All models incorporated the same set of predictors: age, gender, educational level and spectral power within the four EEG frequency bands (Alpha, Beta, Delta, Theta). Student's t-test were conducted to assess group differences.

No significant results were observed when taken into consideration the Total Suggestibility score. However, statistical results were found in all electrodes and in distinct brain lobes when subdividing participants based on Yields and Shift scores.

Specifically:

- *Normalized power on all electrodes*: effect on Theta activity on Yield 2 (t=-1.1, p=.039);
- *Normalized power on parietal areas*: effect of Alpha activity on Shift (t=2.16, p=.04) and Theta activity on Yield 2 (t=-2.62, p=.034);
- *Normalized power on temporal areas*: effect of Alpha activity on Shift (t=2.13, p=.046);
- *Normalized power on occipital areas*: effect of Alpha activity on Shift (t=2.26, p=.035) and Theta activity on Yield 2 (t=-2.69, p=.014).

No significant effects were observed on frontal regions.

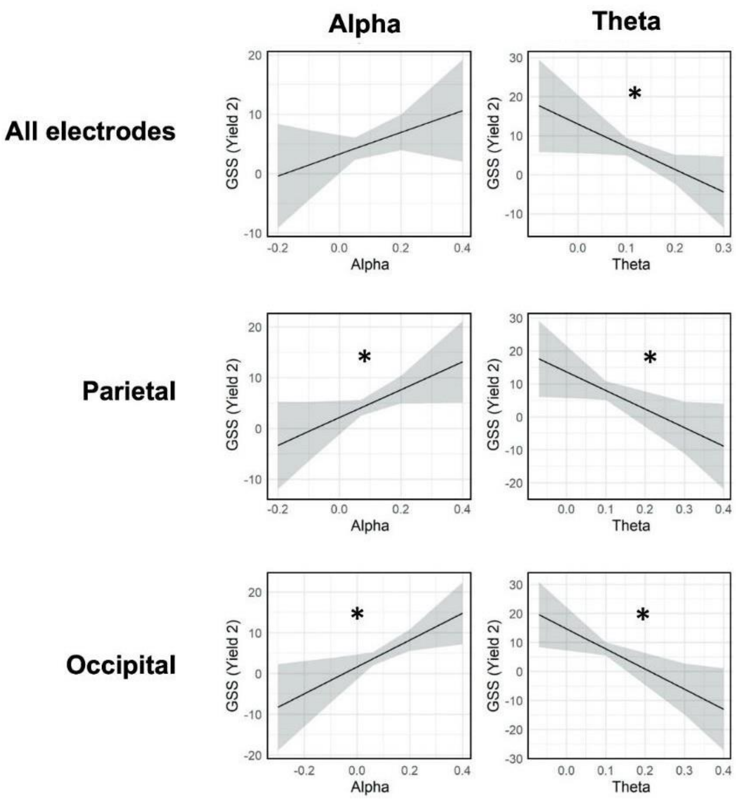


Figure 24. *The graphs display the associations between the Yield 2 score with Alpha (on the left) and Theta activities (on the right). Specifically, the graphs depict the significant positive relation of parietal (t=2.16, p=.04) and occipital () alpha activities on Yield 2 score. Inversely, a significant negative relation of all electrodes (t=-1.1, p=.039), parietal (t=-2.62, p=.034) and occipital (t=-2.69, p=.014) theta activities was found on Yield 2 score.*

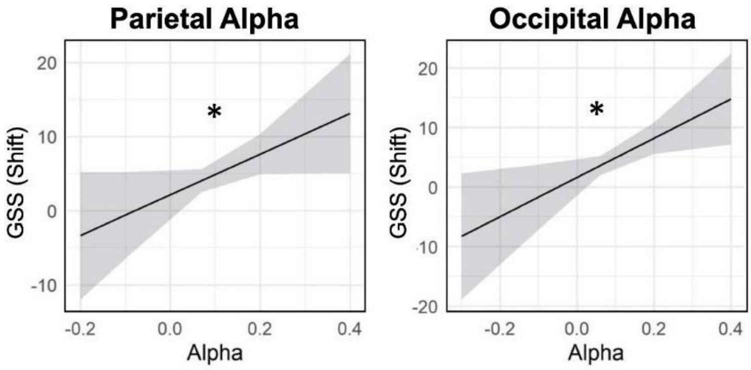


Figure 25. *The graphs show the significant and positive relation of parietal alpha (t=2.16, p=.04) and occipital alpha (t=2.26, p=.035) activities on Shift score.*

3.7.2. GSS and pupil dilation

Analysis with mixed-effects models were conducted. The predictors used were: time bins (500 msec each); GSS levels (High and Low Total Suggestibility scores); interaction between time bins and GSS levels. Demographic variables, such as age, gender and educational level were used as predictors. Student's t-test were carried out to examine group differences on key variables.

A significant difference in pupil dilation between the two groups was found, with greater variability observed in the *High GSS* group (t[113] = 27.16, p < 0.001) (Figure 26).

The analysis demonstrated a significant main effect of time bins on pupil size (Chi-square [119] = 20.436, p < 0.001), but no significant main effect of GSS group itself (Chi-square [1], 2.32, p=0.13). Notably, the interaction between time and GSS level was highly significant (Chi-square [119], 8406,19, p<0.001), indicating that the trajectory of the pupil dilation over time differed depending on GSS level.

The difference between GSS groups was not significant within each time bin, but there was an overall interaction effect, meaning that pupil size changed differently over time depending on GSS level. Specifically, the *High GSS* group seems to have greater pupil dilation, compared to the *Low GSS* group.

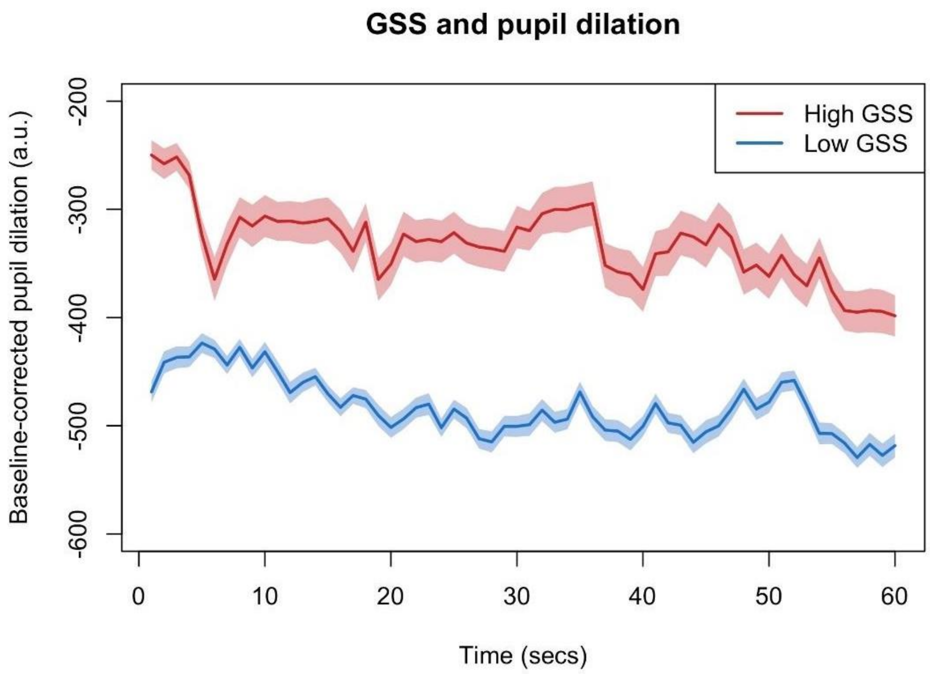


Figure 26. *The chart shows the relationship between Total Suggestibility score (GSS) and baseline-corrected pupil dilation across time (60 seconds). Two distinct curves are displayed: the red line represents the mean pupil among the group with high GSS score, whereas the blue line depicts the corresponding valued for the group with low GSS score. Overall, participants who attained higher Total Suggestibility scores consistently exhibited greater pupil dilation, relatively to those with lower scores ($t[113] = 27.16$, $p < 0.001$). Also, the standard error, represented by the shaded areas, is higher in the high GSS group: this suggests greater variability in pupil size among highly suggestible individuals.*

3.7.3. GSS and pupil frequency bands

For pupil frequency analysis, cleaned and non-downsampled data were analyzed to preserve intrinsic variability.

Given the high correlation between Heart Rate Variability and frequency pupil due to being both regulated by the autonomic nervous system, band definitions were extracted based on canonic HRV bands (Yugar et al., 2023): *Very-low* frequency (VLF): 0-0.04 Hz; *Low* frequency (LF): 0.04-0.15 Hz; *High* frequency (HF): 0.15-0.5 Hz. In scientific literature, other studies have used HRV bands to define pupillary oscillations (Sakamoto et al., 2009; Piu et al., 2019).

Therefore, three bands were defined for this study, (Figure 27): the *Very Slow* frequency band (<0.04 Hz); the *Slow* frequency band (0.04-0.15 Hz); the *Intermediate* frequency band (0.15-0.5 Hz). The first band was labeled *Very Slow* because it is the slowest frequency band detected; the second one was named *Slow*; the third band was labeled *Intermediate,* since previous studies have reported frequencies higher than 0.5 Hz (Montefusco et al., 2022), however, such higher frequencies were not found in this study due to the resting-state condition, as previously documented (Piu et al., 2019).

The Wilcoxon test, a non-parametric version of the Student's t-test for non-normally distributed data, was conducted to assess differences between groups.

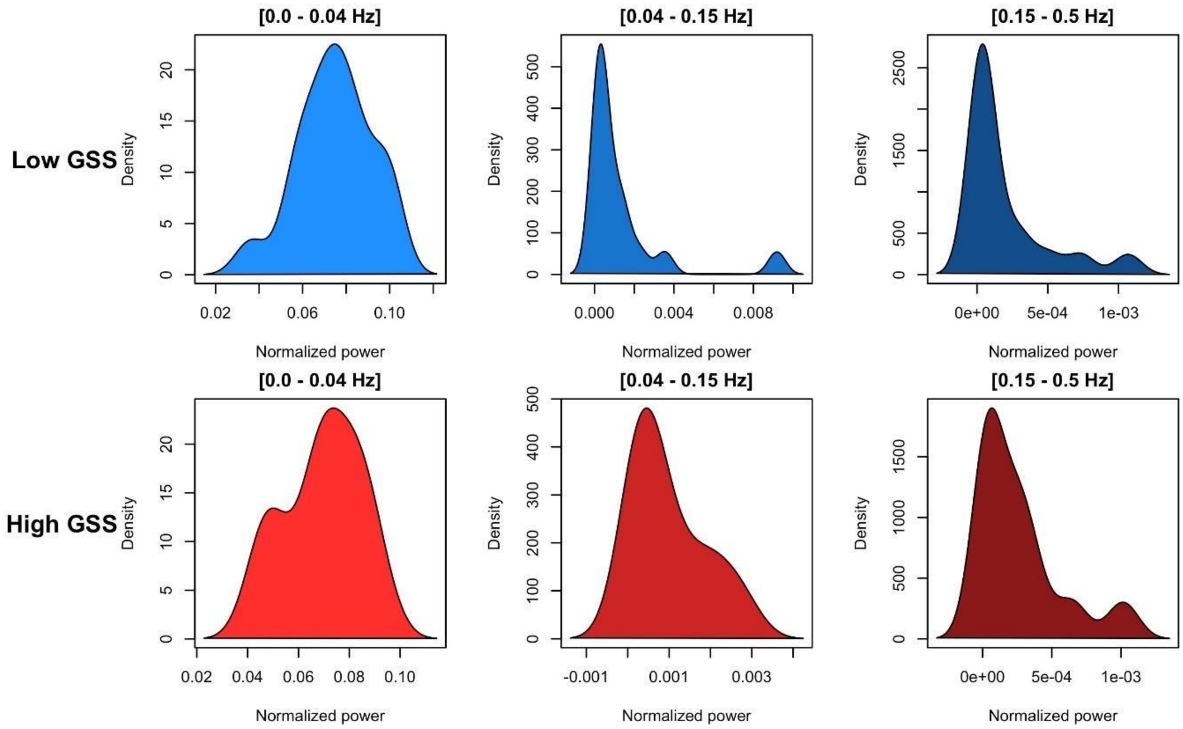


Figure 27. *The graph shows the density of frequency power distributions among the low GSS score group (blue-colored distributions at the top) and the high (red-colored distributions at the bottom). The graphs display: the Very Slow frequency band (<0.04 Hz); the Slow frequency band (0.04-0.15 Hz); the Intermediate frequency band (0.15-0.5 Hz).*

No significant effects were found except for the SI ratio ($W = 57$, $p = 0.047$): lower SI ratio was found in the *High GSS* group in comparison to the *Low GSS* group (Figure 28).

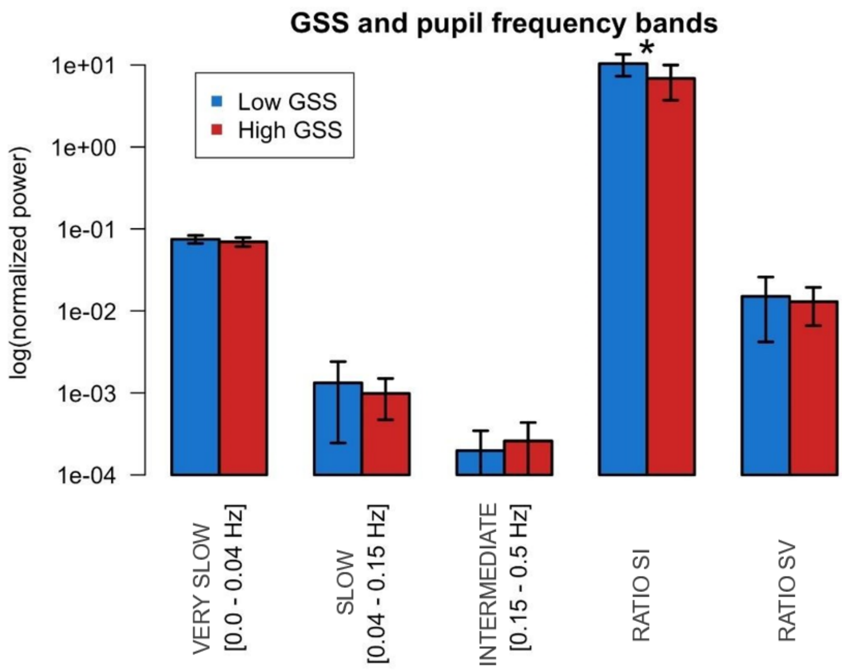


Figure 28. *The bar graph shows the comparison of log-transformed normalized power across distinct frequency bands between the group with low (blue color) and high (red color) Total Suggestibility score (GSS). In the x-axis three pupil frequency bands and two power ratios are displayed: Very Slow (<0.04 Hz); Slow (0.04-0.15 Hz); Intermediate (0.15-0.5 Hz); ratio SI (between Slow and Intermediate bands); ratio SV (between Slow and Very Slow bands). The two groups display comparable frequency power levels, except for the Ratio SI: the low GSS score group is significantly different from the high GSS score group.*

Summary

This chapter was centered on the methodological and statistical aspects of the study.

In the first part, more attention was given to the background data collection (DigitAl lifelong pREvention project), the procedure and the instrumentation utilized. The core focus was directed towards the methods and techniques for this specific study: the Gudjonsson Suggestibility Scale (GSS), the Hd-EEG and the Eyelink Portable Duo eye-tracker. Particular emphasis was placed on the preprocessing cleaning pipeline of both EEG and pupil raw data, notably fundamental to further and more valid data analysis.

In the second part, statistical analyses were conducted by taking into consideration the Total Suggestibility Scale of the GSS in order to subdivide the sample of participants into two groups: those with high suggestibility scores (*High GSS*) and those with low suggestibility scores (*Low GSS*). These two groups were considered in the power spectrum density analysis (EEG), in the pupil size analysis and in the pupil frequency analysis. For the EEG analysis, also the Yield and Shift scores were used to subdivide the sample in individuals with high suggestibility and individuals with low suggestibility.

Significant results were observed. Regarding EEG frequency bands:

- Alpha activity in parietal, occipital and temporal lobes had a positive relation with Shift score;
- Alpha activity in parietal and occipital lobes was positively related to Yield 2 score;
- Theta activity in parietal and occipital lobes was negatively related to Yield 2 score.

On pupil size:

- The *High GSS* group seems to have greater pupil dilation, compared to the *Low GSS* group.

Considering pupil frequency:

- A lower ratio SI was found on the *High GSS* group.

The interpretation and discussion of the described results will be portrayed on the following and last chapter.

CHAPTER 4: DISCUSSION

4.1. Study results' interpretation and discussion

The present study aimed to identify cerebral and pupillometric markers of suggestibility, based on the Cognitive Load Theory framework (CLT). Indeed, it was hypothesized that an individual characterized by high suggestibility may have a baseline *cognitive-load state* (Alm et al., 2019; Farina & Greene, 2020).

Significant results were found, but only supported the initial hypotheses: as expected, higher pupil dilation was associated with the *High GSS* group, indicating the well-established robust link between arousal and pupil dilation.

However, arousal alone cannot fully explain suggestibility in this context. Other CLT and arousal-related hypotheses, such as greater pupil size variability and an increase in sympathetic-related frequency bands were not met.

Actually, contrary to expectations, the observed lower SI ratio in the *High GSS* group in comparison to the *Low GSS* group, indicating a reduced relative power of intermediate frequency oscillations compared to the slow band, suggested a greater parasympathetic dominance relative to sympathetic activity. This could be interpreted as a reduced vigilance level.

Additionally, no significant associations were observed between overall EEG frequency bands and *Total Suggestibility* score.

However, an inverse pattern emerged in alpha and theta bands when taking into consideration the *Shift* and *Yield 2* indices. While a decrease-increase in alpha-theta bands were respectively expected, the opposite was observed. This suggestible group exhibited increase alpha alongside decreased theta power after receiving negative feedback.

4.1.1. The role of coping strategies in suggestibility

What is the plausible explanation of the observed power spectrum results?

Firstly, it is important to recognize that *Shift* and *Yield 2* are two correlated measures, both indicators of resistance to the interviewer's pressure. Therefore, susceptibility to misleading questions may be driven primarily by emotional factors related to coping strategies rather than a *baseline cognitive-load* status.

Tracing back to Gudjonsson's (2003) seminal work, coping strategies were highly related to suggestibility (Figure 1). Indeed, emotion-focused coping strategies measured by COPE subscales (Billings & Moos, 1981) are predictive of tendencies to yield to suggestive forms of questioning (Bain et al., 2015). These strategies were found to redirect cognitive resources toward emotional regulation, impairing the management of emotion from the task of accurate recall making it more difficult to detect misleading information.

Supporting this view, several studies have observed significant results in alpha and theta waves related to emotional coping.

A study of Allegretta et al., (2024) addressed emotion regulation within the framework of psychological stress dynamics. Specifically, it explored the associations between emotion regulation processes, such as interoceptive awareness (MAIA) (Mehlig et al., 2012), cognitive reappraisal (EROS) (Nivel et al., 2011) and mindfulness (FFMQ) (Baer et al., 2005), and electroencephalographic markers of psychological stress response. Significant positive correlations were observed between interoceptive awareness measures and alpha activity temporo-central and occipital-parietal regions. Moreover, theta activity positively correlated with the "Act of awareness" subscale of the FFMQ, implicating theta rhythms in enhanced attentional capacity, cognitive mode of deliberate response formulation and reflective cognitive states.

These results (Allegretta et al., 2024) have major implications for the interpretation of the findings in the present study. Firstly, Allegretta et al., (2024) observed that both alpha and theta waves were more prominent in temporo-central and occipito-parietal regions. Similarly, in the present study, these areas showed significant correlations with *Yield 2* and *Shift* measures.

The observed negative correlation between theta power and *Yield 2*, where individuals answer affirmatively with incorrect answers following the negative feedback, aligns with Allegretta et al. (2024). Specifically, individuals who are more susceptible to interviewer influence tend to engage less in reflective cognitive processing and are more likely to respond on the basis of emotional impulses.

The interpretation of the effects of alpha power, however, presented greater complexities: in the present study, alpha wave activity was significantly and positively associated with *Yield 2* and *Shift* scores, while in Allegretta et al. (2024) reported a positive association with interoceptive awareness. It is indeed expected that individuals who adopt this coping mechanism enhance their capacity to respond appropriately to varying emotional contexts, resulting in a less susceptible behaviour in response to interviewer's pressure. Although interoceptive awareness (IA) is commonly associated with improved cognitive processes, other studies have found positive correlations between IA, emotional reactivity, negative affectivity and trait anxiety, which are related to fear of negative evaluation (Pollatos et al., 2007; Durlik et al., 2014). These factors play a critical role in the context of the Gudjonsson Suggestibility Scale administration following the interviewer's negative feedback. While it is commonly assumed that interoceptive abilities facilitate regulation of negative emotions, a study conducted by Zamariola et al. (2019) that collected a huge sample of participants (n = 534) found no support for this widely held assumption, both in a frequentist and bayesian framework. Actually, evidence indicated that heightened attention to bodily sensations may be associated with disrupted emotion regulation (Zamariola et al., 2019; Palser et al., 2018).

In conclusion, while arousal and therefore a higher baseline *cognitive-load* seems to be implicated in suggestibility given the promising results in pupil dilation, it does not fully account for its multifaceted nature.
Actually, the observed high alpha activity is an indicator of low arousal (Codispoti et al., 2023), associated with reduced concentration, which may explain the tendency to yield and display less resistance to the interviewer's pressure (Surova et al., 2021), alongside greater internal attention and diminished processing of external stimuli (Foxe & Snyder, 2011). Therefore, individuals who are more susceptible to interviewer influence may display a tendency to adopt strategies which are more inclined to passive acceptance of external suggestions. Indeed, the influential role of coping strategies in modulating suggestibility emerges as particularly salient (Allegretta et al., 2024).

4.2. Strength and limitations of the experimental settings

This thesis presents its strengths and limitations. On one hand, the study offers an innovative perspective by investigating potential biomarkers of interrogative suggestibility, a largely underexplored area. Such findings hold important to give new insights for enhancing the conceptual understanding of suggestibility. Additionally, and contributing to more tailored assessment protocols for a more vulnerable cohort, represented by elderly individuals.

On the other hand, the present study presents various limits:

- Limited sample size (n = 29).
- GSS-2 administered from two different administrators (n = 20 for administrator 1; n = 9 for administrator 2).
- The administration of the CRI-Q to evaluate cognitive reserve prior to the delayed recall of the GSS may have elicited negative biases regarding cognitive abilities, potentially influencing suggestibility results.
- A subdivision of participants in *High GSS* and *Low GSS* based on the median of the sample and not normative values (Bianco & Curci, 2015).
- No fixation cross in the resting-state condition that could have altered the participants' pupil size.
- Slight variations in brightness filtered through the curtains over the months that could have influenced the participants' pupil size.

4.3. Future perspectives

Further research evaluating suggestibility in healthy elderly individuals could implement:

- A fixation cross during resting state periods, to obtain a more accurate measurement of pupil size.
- Pupillometric measurement during the administration of the Gudjonsson Suggestibility Scale. The use of a wearable eye-tracker in assessing Interrogative Suggestibility represents a promising approach to directly observe the immediate effects of suggestibility on pupil responses. This could be interesting to see the correlation between and baseline pupil size measured in a resting state condition.
- Analysis of eye movements in a free viewing task. Recent research has found two distinct viewing styles that correlate with distinct cognitive profiles: *Dynamic* and *Static* (Zangrossi et al., 2021). Particularly, *Dynamic* viewers tend to present more impulsivity, a factor positively correlated with suggestibility (Gudjonsson, 1984).

In light of the unexpected results derived from power spectrum analysis, further research might consider to incorporate additional measures to explore the relationship between coping strategies and suggestibility. Specifically, in relation to the study of Allegretta et al. (2024) the following questionnaires could be implemented:

- The *multidimensional assessment of interoceptive awareness (MAIA)* to evaluate interoceptive awareness in the individual (Mehling et al., 2012).
- *Five Facets Mindfulness Questionnaire (FFMQ)* to evaluate with particular attention to the subscale "Act of awareness" (Baer et al., 2006).

4.4. Forensic applications

Interviewing elderly witnesses presents unique challenges, especially considering the potential for unreliable testimony. The natural cognitive decline, particularly within source monitoring, translates in a more-likely increasing in false recollections. Beyond that, in light of these study results, the role of emotions and the ways in which individuals regulate them are of significant importance.

Therefore, there is a pressing need to support elderly witnesses to ensure accurate testimony and to implement appropriate procedures in the approach of police and court officials.

Recognizing the heterogeneity of ageing processes and suggestibility among elderly individuals further highlights the need for individualized and tailored interviewing approaches. Best interviewing practices, which are constituted by rapport building, establishing ground rules, encouraging free recall via open-ended questions, and positive interview closure, demonstrate promise in enhancing recall accuracy and mitigate the effects of misleading questions (Holliday et al., 2012).

CONCLUSIONS

The present study aims to contribute to the extensive body of research exploring the multifaceted construct of suggestibility. Particular attention was posed to Interrogative Suggestibility, since it is more implicated in forensic context. In this sensitive field, relying on more scientifically grounded physiological data derived from cognitive neuroscience, such as brain rhythms and pupil size, can translates into support when interviewing elderly individuals. As often remarked, with reference to the points outlined in the introduction, suggestibility varies among elderly individuals and is not solely age-dependent. In fact, it is influenced by a combination of cognitive, trait and situational factors that need to be taken into account when assessing testimonial validity.

Therefore, are there any other methods that would measure suggestibility and enhance the assessment of testimonial validity? Are brain rhythms and pupil size accurate physiological indicators of suggestibility?

In response to the questions formulated in the introduction of this study, a cautious approach is recommended. On one hand, it is true that significant results were found in pupillometric measures. On the other hand, no significant results were found in brain rhythms when relying on CLT, addressing the need to rely on other validate frameworks to understand underlying cerebral mechanisms of suggestibility. The construct's multidimensional core characteristic encompasses various theoretical frameworks and factors, such as the critical role of coping strategies. The role of emotions and the strategies employed to manage them seem to be pivotal in determining responses to interviewer-induced pressure.

However, further research is required to confirm the promising *biomarker* validity of pupil size in suggestibility, while more studies grounded in alternative theoretical frameworks could enhance understanding of brain rhythm dynamics.

With the aim that this knowledge could be translated into tailored interventions when assessing testimonial accuracies of healthy elderly individuals, recognizing the complex interplay of cognitive, social, emotional and interpersonal factors on suggestibility is a necessary step.

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