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SETÚBAL**

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**Exploring the Neural Mechanisms
Behind Language Processing:
Contributes regarding the effects of
bilingualism and lateralization in
handwritten tasks**

Relatório de Dissertação/projeto/estágio/projeto
de investigação do Mestrado em

Engenharia Biomédica

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November 2024

Acknowledgments

First and foremost, I would like to thank my family who supported me through thick and thin, who kept me in check and made sure that I would be able to complete all of it.

My coordinators, professor Anna Letournel and professor Dina Caetano Alves, who were there to help and clarify any of my doubts, to lead me in the right way and for making me keep pushing it and become better until the very end. Also appreciate every teacher who has helped by making every situation in the laboratory clearer and easier to understand. An additional appreciation to Faculdade de Ciências da Universidade Nova de Lisboa for providing the conditions and the equipment to produce the study, as well as Letícia Almeida that made available the bilingual questionnaire.

One of the biggest thanks goes to my girlfriend, Diana, one of my biggest supporters, who made sure I would not burn out and assured me that in the end everything is going to be all right and kept helping me to become a better person.

My friends, who I know that in the end even if every goes south they will be there to make sure that I will be able to go back on track and to those moments where a helping hand was needed and from there countless hours of free therapy.

To everyone at my workplace that made sure that I would be able to make it through until the end by helping me with scheduling everything and making me feel comfortable not only to be able to work but also to attend any meeting or to keep my focus on the project.

Abstract

Handwriting skills are categorized into fluency (speed and stroke duration) and legibility (ease of readability), which involves coordination between cognitive and perceptual-motor skills, with the latter encompassing visual perception and fine-motor coordination. Difficulties in handwriting are often associated with developmental disorders or neurodegenerative diseases like Alzheimer's, which can lead to poor control of fine-motor skills and spatial organization. These difficulties arise due to complex interactions between biomechanics and brain areas responsible for control and memorization, particularly working memory which plays a significant role in writing performance, facilitating manipulation and maintenance of information during writing tasks. Bilingualism shapes brain structure and neuroplasticity, influencing visual word recognition, gray matter development, and the organization of languages based on proficiency and age of acquisition. Electroencephalography (EEG) studies neural dynamics during handwriting production, revealing differences between right- and left-handed individuals and aiding in early dementia screening. Electromyography (EMG) records muscle activity during handwriting, providing insights into handwriting interventions for conditions like Parkinson's disease and grip-related muscular changes due to how the subject writes and grabs the pen during writing.

The results include distinct neural activation patterns across different frequency bands, such as delta, theta, and alpha waves, reflecting cognitive and motor processes. Muscle artifacts were observed in the beta and gamma range, which impacted data quality. The study highlights the involvement of frontal and parieto-occipital regions in tasks requiring motor coordination and language processing, with more complex tasks, like morphological analysis, engaging broader brain networks.

Keywords: Electroencephalography, electromyography, handwriting, network connections.

Resumo

As competências de escrita manual são categorizadas em fluência (velocidade e duração dos traços) e legibilidade (facilidade de leitura), envolvendo a coordenação entre competências cognitivas e preceptivo-motoras, sendo estas últimas relacionadas com a percepção visual e a coordenação motora fina. As dificuldades na escrita manual estão frequentemente associadas a complicações do desenvolvimento ou a doenças neurodegenerativas como a doença de Alzheimer, o que pode resultar num controlo deficitário das competências motoras finas e da organização espacial. Estas dificuldades surgem devido a interações complexas entre a biomecânica e as áreas cerebrais responsáveis pelo controlo e pela memorização, particularmente a memória de trabalho, que desempenha um papel significativo no desempenho da escrita, facilitando a manipulação e a manutenção de informações durante as tarefas de escrita. O bilinguismo molda a estrutura cerebral e a neuroplasticidade, influenciando o reconhecimento visual de palavras, o desenvolvimento da matéria cinzenta e a organização das línguas com base na proficiência e na idade de aquisição. Estudos de eletroencefalografia (EEG) analisam as dinâmicas neuronais durante a produção da escrita, revelando diferenças entre indivíduos destros e esquelinos, além de contribuírem para a deteção precoce de demências. A eletromiografia (EMG) regista a atividade muscular durante a escrita, fornecendo informações sobre intervenções relacionadas com condições como a doença de Parkinson e alterações musculares associadas à pega com a mão.

Os resultados incluem padrões de ativação neural distintos em diferentes bandas de frequência, como as ondas delta, teta e alfa, que refletem processos cognitivos e motores. Foram observados artefactos musculares na gama beta/gama, o que afetou a qualidade dos dados. O estudo destaca o envolvimento das regiões frontal e parieto-occipital em tarefas que requerem coordenação motora e processamento da linguagem, sendo que tarefas mais complexas, como a análise morfológica, envolvem redes cerebrais mais amplas.

Palavras-chave: Eletroencefalografia, eletromiografia, escrita, conexões em rede.

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Acronyms

AD – Alzheimer’s Disease

CSSHL – Congenital Severe Sensorineural Hearing Loss

EEG – Electroencephalography

EMG – Electromyography

fMRI – Functional Magnetic Resonance Imaging

ICA – Independent Component Analysis

L1 – Primary Language

L2 – Secondary Language

PFC – Prefrontal cortex

1. Introduction – Neurophysiologic and psycholinguistic aspects of (hand)writing

Handwriting is a multifaceted process that involves a combination of cognitive and perceptual-motor skills, where the latter includes visual perception and fine-motor coordination (Lu et al., 2024; MacMahon & Charness, 2014) being needed to understand the neural networks that binds all the skills together this work focuses on exploring the neural and motor mechanisms of handwriting in order to improve diagnosis and interventions at earlier stages. The structure includes an introduction to handwriting's cognitive and neural bases, followed by chapters on research methods, findings related to handedness, bilingualism, and neurodegenerative diseases, and concluding with practical applications and future research directions. The interactions between cognitive, motor and sensory skills culminates in what is known as visual-motor integration, requiring a blend of perception, dexterity, and motor planning. Difficulties in these areas are often linked to developmental disorders or neurodegenerative diseases such as Alzheimer's Disease (AD), where patients exhibit poor control over fine-motor skills and spatial organization. These impairments result from the complex interplay between biomechanical functions and brain regions responsible for motor control and memory (Cilia et al., 2024; Downing & Caravolas, 2023). Perceptual-motor skills, which are essential for handwriting rely heavily on cognitive and motor functions, these are divided into two primary categories: fluency, which refers to the speed, velocity, and stroke duration of writing, and legibility, which pertains to how easily the handwriting can be read (Downing & Caravolas, 2023). Both fluency and legibility are influenced by motor control, cognitive processes, spelling, and the attention devoted to writing. These factors can be affected by aging, personality traits, habits, and neurological conditions (Chaudhari & Thakkar, 2019). Neuroscientific research has mapped the brain regions involved in handwriting, identifying the premotor cortex, precentral, superior, and middle frontal gyrus as key areas (Rech et al., 2020). Neuroimaging studies during orthographic tasks reveal that a predominantly left-hemisphere network, particularly the middle frontal gyrus, superior parietal area, and right cerebellum, are specifically activated during writing. These regions are complemented by other areas related to motor, linguistic, and sensorimotor processes (Planton et al., 2013).

The impact of neurodegenerative diseases on handwriting has been explored, particularly in conditions like Parkinson's disease, which affects writing rhythm, character form, and spacing due to tremors and motor variability (Walton, 1997). However, despite these challenges, the cerebellum plays a compensatory role in internal timing mechanisms (Cilia et al., 2024). Furthermore, "handedness" significantly influences how the brain organizes during writing, with distinct lateralization patterns observed between right- and left-handers (Goffin et al., 2019). This lateralization is particularly evident in tasks such as copying versus writing, where different brain areas are involved despite similar neural pathways being activated (Matsuo et al., 2000).

Language also plays a crucial role in handwriting, especially in bilingual individuals, where the acquisition and use of multiple languages affect both structural brain organization and neuroplasticity as well as linguistic properties affect linguistic performance, orally and/or in writing (Alves, 2012), in context of language and pathology development. Bilinguals often show differences in brain activity during language tasks, with the left parietal cortex and prefrontal regions being particularly involved (Van Heuven et al., 2008; Zhao et al., 2023). These differences highlight the complex neural organization of languages and the additional cognitive demands faced by bilinguals during handwriting (Liu & Cao, 2016). Memory, particularly working memory, is another central cognitive resource in handwriting. It is essential for the manipulation and maintenance of relevant information during writing tasks (Baddeley, 2003; Linden, 2007). Working memory is especially critical for tasks such as translation and revision in writing, with orthographic working memory playing a key role in differentiating between typically developing individuals and those with dyslexia (Mo et al., 2018). Long-term memory is also essential for recalling the sequence of strokes needed to form characters and words (Pei et al., 2021a).

To study the neural dynamics of handwriting, techniques like electroencephalography (EEG) have been employed, revealing distinct patterns of brain activity associated with different writing tasks and conditions. EEG studies have shown increased connectivity bilaterally, during handwriting with non-dominant hand (Pei et al., 2021b), and have been used to screen for conditions like dementia and Parkinson's disease (Kamran et al., 2021). Similarly, electromyography has been used to analyze the muscular activity involved in handwriting, providing insights into how different grips and muscle groups are engaged during writing tasks (Loconsole et al., 2019). This

technique is particularly useful in studying conditions like Parkinson's disease and writer's cramp, where altered muscle activity patterns are observed (Salatino et al., 2019). In addition to motor and cognitive factors, sensory aspects such as vision and hearing also play significant roles in handwriting. For instance, eye movement studies have shown that visual fixations during writing help guide hand movements, influencing the rhythm and spacing of written words (Sita & Taylor, 2015). Hearing impairment, on the other hand, can impact cognitive functions and handwriting skills, particularly in individuals with auditory processing disorders (Rashid et al., 2018).

Overall, the study of handwriting, particularly in populations with neurodegenerative diseases or developmental disorders, requires a multidisciplinary approach that includes cognitive neuroscience, motor control, and sensory processing. Tools like Smart Pens, EEG, and electromyography (EMG) provide valuable data for understanding the complex interactions between brain, muscle, and sensory systems during writing tasks. Ultimately these tools help identify and address the challenges faced by individuals with impaired handwriting skills.

Some studies devoted to motor mapping over electrostimulation were able to report that the areas on our brain responsible for writing are mostly localized at the premotor cortex, over the precentral, superior and the middle frontal gyrus (Rech et al., 2020), in addition it has been shown that mainly left-hemisphere network of cortical and subcortical areas are obtained when analyzing neuroimaging during orthographic processes where the middle frontal gyrus area, the superior parietal area and right cerebellum are considered writing-specific and other areas being related to non-specific motor, primary motor and sensorimotor cortex, or linguistic processes, ventral premotor cortex and posterior/inferior temporal cortex (Planton et al., 2013), in the end this study was able to confirm a crucial involvement of the left frontal and superior parietal regions. Others tried to relate and determine neurodegenerative diseases such as Parkinson, affecting the rhythm and variability in characters forms and spacing produced during writing tasks as well clear tremors forming wavers (Walton, 1997) however the cerebellum compensates in internal timing mechanisms (Naro et al., 2022), and Alzheimer by pattern recognition making people draw spirals and write sentences in Czech, these tests help by providing information about how much the diseased as progressed (Sarin et al., 2023). On this topic the term “handedness” was great value since as described the brain will operate differently when writing with the dominant or

non-dominant hand. Since at a brain level people who use their right hand show a left-lateralized effect within the intraparietal sulcus as for left-handers it is a reverse lateralization (Goffin et al., 2019), data acquired by the usage and analysis of a functional Magnetic Resonance Imaging (fMRI). There is also a difference at a neurological level when the task is to copying letters as to writing, although they activate similar pathways they differ in terms of the involvement of the right superior parietal lobule, less activated during writing tasks, and the left inferior frontal gyrus for phonological processing and language production (Matsuo et al., 2000).

1.1. Memory and Language

Memory is considered a central cognitive resource in writing performance since it is involved in the manipulation and maintenance in active attention of relevant information and inhibition of irrelevant information (Vasylets & Marín, 2021). In addition memory contributes to hand-eye coordination essential for precise and controlled handwriting and letter formation helping individuals remember the shapes and strokes to form the letters. Working memory, known as the temporary storage and manipulation of information necessary for complex cognitive activities and associates the cortex in the frontal lobe and parietal lobes (Baddeley, 2003; Linden, 2007). Working memory influences the translation and revision processes involved in writing, including tasks such as note-taking and reasoning (Kormos, 2012). A specific subset as orthographic working memory that combines the phonological or orthographic loop with executive functions which can differentiate typically developing individuals from the ones with dyslexia (Mo et al., 2018). The brain also relies on long-term memory when forming the sequence of strokes needed to form the character or the word itself. Research suggests that the processing of initial and non-initial strokes is expected to be different: initial strokes are often associated with memory retrieval as the non-initial ones are associated with executive activities (Pei et al., 2021a). Short-term memory plays a role in processing of lengthier units and synthetic structures (Güvendir & Uzun, 2023).

1.2. Bilingualism

When it comes to writing, language takes a crucial part in it since it can enhance their academic, linguistic and literacy-related knowledge (Kibler, 2010). In bilingual individuals, the acquisition of multiple languages affects both structural brain

organization and neuroplasticity (Zhao et al., 2023). However bilingual people may experience interference with visual word recognition (Vasilyeva, 2021). The presence of a second language is associated to the increasing of grey matter in the left parietal cortex which is affected by the proficiency and age of acquisition. Starting to learn a second language at a younger age is advantageous, as individuals who acquire a language later achieve a lower level of proficiency, which plays a significant role in second language organization (Perani, n.d.; Zhao et al., 2023). In a study by (Wartenburger et al., 2003) they compared the results between these two groups (early and late learners). When it came to grammar the late acquisition group showed a bilateral activation in the inferior frontal gyrus, involving the operculum and the basal ganglia, but no differences in the semantic tasks. The main brain region associated with executive control is the prefrontal cortex (PFC), is involved in a wide variety of cognitive and language related functions, such as working memory, controlled semantic retrieval, phonological retrieval, selection of task-relevant information, conversion and lexical search, hierarchical control, and unification for language (Van Heuven et al., 2008). These findings suggest that the neural organization of languages depends on both the quality and frequency of exposure to the language, as well as the timing of acquisition.

It is necessary, however, to take into consideration the role of bilingualism since the majority of the population is fluent in two or more languages. This raises the question “How is the language network in the brain is organized” (Van Heuven et al., 2008). The brain functions differently if writing in the native language compared to when writing in the foreign language. Studies have shown that secondary language (L2) processing involves additional region than primary language (L1), especially for late bilingual than early ones (Liu & Cao, 2016) as the latter have greater activation in the left fusiform gyrus than late bilinguals during L1 processing. Anatomical connectivity also differs, especially when it comes to sounds. For bilinguals the left insula presents more activity than for monolinguals as well the left inferior prefrontal language regions in the inferior frontal gyrus have shown more activation in bilinguals than monolinguals when performing language tasks (García-Pentón et al., 2014). A study by (Kogan et al., 2020), participants were asked to copy manual action verbs, with the speed of hand movements impacted by the way of processing or thinking about the actions, the authors analyzed motor planning and execution dynamic by evaluating the data originated from

the first-letter lag, time lapse between word presentation and keystroke, and whole-word lag, time lapse between first and last keystroke. The study found that the writing of the action verbs was more facilitated in Spanish, native language, than in English, foreign language, suggesting differences in word processing, semantic demands, and motor network activation account for this. This also related to the concept of “language conflict” (more common during speech) where bilinguals commit errors when selecting the intended language occurring a cross-language situation. This conflict can be resolved in two ways; the first, selecting the words from both languages and then processing and selecting the correct one from the target language representation; the second, a blockage mechanism as the nontarget language does not suffer activation (Van Heuven et al., 2008). In a lexical decision task, bilinguals (English and Dutch) showed greater activations in the left-inferior prefrontal cortex as well the superior frontal gyrus and showing an activated cluster on the parietal lobule suggesting a high sensitivity in this region. The impact of bilingualism on language processing has also been studied in relation to, pseudowords, non-meaningful pronounceable letter strings that conform to phoneme-grapheme conversion rules, and are often used to assess phonological spelling (Afonso et al., 2020; Planton et al., 2013; Suggate et al., 2023) found that bilinguals showed stronger activations in the medial frontal gyrus, left-inferior prefrontal cortex and the left lingual gyrus for bilinguals during English lexical tasks when compared to the English monolingual controls. Lexical effects were found in the left parietal lobule and the left middle temporal gyrus. On the other hand, monolingual participants presented stronger activations for words than pseudowords in the left anterior middle frontal gyrus and the left superior temporal gyrus. No regions were more activated for pseudowords than for words in both monolinguals and bilinguals during the generalized lexical task. In another study children were asked to complete some tasks to study handwriting speed and its relationship with graphic speed and spelling. The test included a total of 48 stimuli, 24 words and 24 pseudowords. The test showed lexicality problems for the pseudowords (Afonso et al., 2020). Children with developmental dyslexia had difficulty pronouncing pseudowords and spell written words (Berninger et al., 2015). Pseudowords do not carry semantic content contrary to words engaging different brain mechanisms, suggesting that words and pseudowords are processed differently. The neural responses vary depending on how these stimuli are associated with specific outcomes (gains or losses) (Kulke et al., 2019). As for the stimuli (D. Alves et al., 2017; D. C. Alves, 2012; Carvoeiro, 2017) portrays writing as

learned skill that accompanies students throughout their academic and social lives impacting the child's development.

1.3. Electroencephalography

To better understand these processes the usage of electroencephalography (EEG) is a valuable tool for capturing neural dynamics of visual-motor processing during handwriting production (Loh et al., 2024). EEG signals, particularly from the occipital region, have been used to investigate neural connections in right-handed and left-handed people (Andrew Ng & Leong, 2014). to determine the connections made when compared to right-handed and left-handed people, their work proved to exist more connections between hemispheres especially for left-handed individuals. The usage of the left hand shows an activity of the basal ganglia and primary motor area indicating coordination inter-hemispheric connectivity with the parietal-frontal cortices when speaking about non-dominant left-handed movements (Tsurugizawa et al., 2023). When left-handed individuals used their non-dominant hand, activity was observed in basal ganglia and the (Chai et al., 2023) used EEG to assess sensorimotor cortical activity in primary care setting following the international standard 10-20 electrode system. Like other studies the waves acquired by the EEG correspond to the β (beta), α (alpha), θ (theta) and δ (delta) frequency bands.

The main EEG frequency bands include: delta waves (0.5 to 4 Hz) typically associated with deep sleep (Miraglia et al., 2021), restorative processes, and unconscious states (Hussin & Sudirman, 2013; Molaee-Ardekani et al., 2010); theta waves (4 to 8 Hz) often linked with light sleep, relaxation (X. Chen & Zhang, 2025; Y. Li et al., 2024; Vergara-Martínez et al., 2021), deep meditation, and states of creativity or subconscious thought, in awake individuals, theta activity is typically observed during moments of relaxation (Goldschmied et al., 2019); alpha waves (8 to 12 Hz) are typically present when a person is in a calm, relaxed, but alert state (Hussin & Sudirman, 2013); beta waves (12 to 30 Hz) associated with active thinking, problem-solving, alertness, and concentration (Q. Chen et al., 2025; Eskikurt et al., 2024). These waves dominate when a person is engaged in cognitive tasks, active mental processing, or stress; gamma waves (30 to 100 Hz) represent the fastest brain activity and are associated with higher cognitive functions such as learning, memory, attention, and sensory processing (Eskikurt et al., 2024b; Whitham et al., 2007, 2008). Beta and

gamma waves share overlapping roles in cognitive and motor functions, contributing to a unified understanding of brain activity (Ma et al., 2022). As such, these oscillations will be studied together to capture their combined influence on neural processes.

A study conducted by (Heimann et al., 2013) investigated how perceiving written language symbols activates the motor hand representation in the brain. Using a high-density EEG, researchers measured cortical motor activation while participants observed Roman letters, Chinese characters, and scribbles. The results showed motor activation in both hemispheres for all stimuli with stronger activation on the left side. Scribbles triggered faster motor response compared to symbols which suggests that recognizing stimuli as hand gestures may drive motor activation. These differences may reflect visual-motor effects. The utility of EEG extends beyond comparison of hand dominance as it can also provide insights into neurological conditions. (Marques Paulo et al., (2024)) studied patients with focal dystonia and found altered connectivity between the supplementary area and the left sensorimotor cortex during handwriting. EEG is also valuable in detecting Parkinson's disease (PD) early, helping to slow down the progression (Dehghanpur Deharab & Ghaderyan, 2022). It has been found to offer high accuracy for identifying PD, with specific patterns of brain activity associated with micrographia due to stiffness, cramp writing and tremor. Neural networks and deep learning methods have been as early detection and diagnostic tools for PD (Kamran et al., 2021). Another important application of EEG is in assessing functional connectivity during motor imagery of writing in writer's cramp (Thirugnanasambandam et al., 2020) confirmed that the bilateral sensorimotor regions are critical for motor imagery of writing in these. Similarly, EEG has been used to study the differences in brain activity during writing between right-handed adults with dyslexia and a healthy control (Perera et al., 2018) recorded EEG signals while participants wrote a paragraph. Electrodes were placed on the anterior-frontal lobe being mentioned as the optimal channels for writing and by comparing the results the authors concluded that the EEG channels responsible for producing unique brainwave signals in individuals with dyslexia compared to normal controls was the frontal lobe (F5, F3, FZ, F4, F6) as shown in Figure 1.

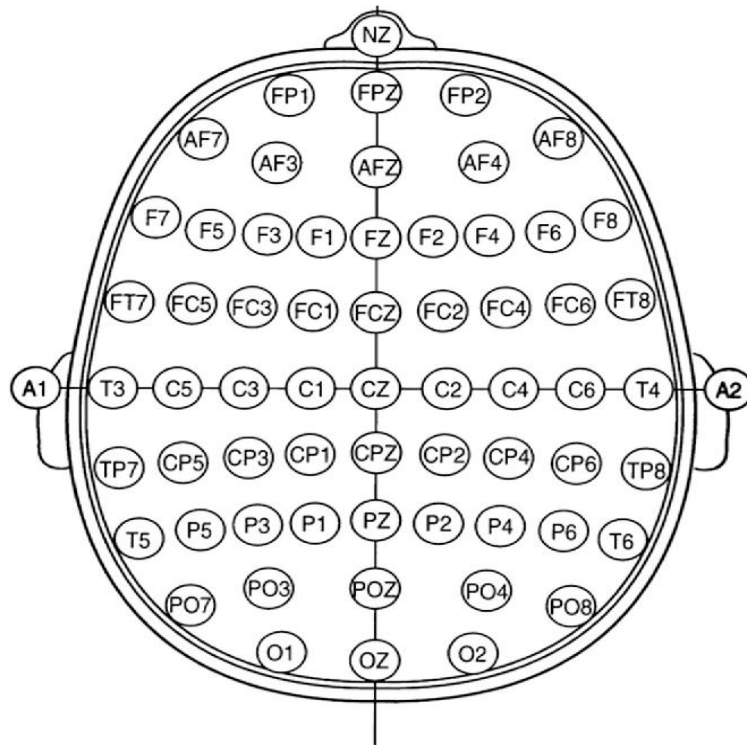


Figure 1 10-20 international electrode system, Source: (Nuwer, 2018)

In contrast a study made by (Institute of Electrical and Electronics Engineers Malaysia Section et al., (n.d.)) recorded signals during writing and grasping with electrodes placed in the central and parietal lobes from the channels (C3, C4, P3 and P4). This study focused on sensory-motor functions, perception, and differentiation. The frequency ranges of EEG signals obtained during writing for dyslexic children is between 22 and 28Hz dyslexic children use more energy and produce high frequency of beta wave when compared to their non-dyslexic peers (Institute of Electrical and Electronics Engineers Malaysia Section et al., n.d.).

1.4. Electromyography

Another instrument that will help with evaluating a person writing skill with both hands is the EMG which allows the analysis of the muscular activity during handwriting tasks (Loconsole et al., 2019). EMG is a useful and practical non-invasive method which records the electrical potential generated by the muscles, despite them being sensitive to disturbances like sweat and hair (Chihi et al., 2020). EMG allows coordination between the handwriting and the muscle movements by capturing signals from the hand and forearm. A study made by (Latimer et al., (2024)) used two EMG sensors, to explore handwriting interventions for people with Parkinson's disease. The

sensors were placed on the first dorsal interosseus (between the thumb and the indicator finger) and extensor digitorum comunis located in the forearm. In another study conducted by (Farris et al., (2022)) explored the relationship between muscle activation and handwriting quality focusing on all the muscles required to complete the writing task being the flexor carpi ulnaris, flexor carpi radialis, extensor carpi ulnaris, extensor carpi radialis, flexor pollicis brevis, and the upper trapezius. However, it must be considered the type of grip used by the individual. People who often use a tripod grasp show different changes in the EMG activity (Chang et al., 2015). For example, individuals with a static tripod grasp show increased activity in the proximal muscles, which may indicate muscular harm during the progression in academic life (P. H. T. Q. de Almeida et al., 2013; Baur et al., 2009). When it comes to disease treatments, this equipment has been used to study the differences in writing between healthy and diseased individuals, in a study by (Salatino et al., 2019), EMG was used to assess the effectiveness of the repetitive transcranial magnetic stimulation to amend focal hand dystonia symptoms. Patients with writer's cramp tend to have increased muscular activity however not showing correlation with the cerebral activity (Delnooz et al., 2012). Specifically, the study found reduced intrinsic coupling between the left dorsal precentral region, which is responsible for writing movements and a left superior parietal region.

Focus and attention are also critical when discussing writing. They help provide a perception about what or where is the individual looking which in turn can influence the activity and intensity of different brain areas (Hacker et al., 2017). Writing is a crucial skill in someone's life and students are trained in different postures which can affect the speed and quality of the writing (Yang et al., 2020). In 2006, a study by (Written, 2006) tested a device for "Eye and Pen" to study reading during writing. The eye tracker transmitted spatial and temporal data revealing the direction of the gaze during writing and pauses. A study conducted by Sita & Taylor, (2015) examined eye movements during handwriting and reading. They found that the participants produced more fixations during writing and for longer periods of time, these fixations were for each letter and focused around base of the letters. Additionally, there were more fixations when words were written individually compared to within sentences. The authors also concluded that the eye movement not only helps with reading the text being written but to guide hand movements influencing the rhythm and spacing of the written

words. Other study investigated the visual-motor coordination of preschool and early elementary school children as they copy familiar (English letters) and unfamiliar (Cyrillic symbols) letter-like forms. The results show that children copied familiar English letters more efficiently than unfamiliar Cyrillic symbols, spending more time and making more visual fixations on the latter (Fears & Lockman, 2018). In general, it is observed that the application of EMG techniques in this area remains limited, highlighting the need for further studies to deepen knowledge in this direction.

1.5. Variables in consideration during EEG studies

Another important factor to consider is the individual's hearing ability, as the person needs to be able to hear and respond properly. This factor needs to be studied since the study will require the volunteers to hear a word and write it down immediately after. Hearing impairment can be associated with cognitive decline and brain atrophy (H. F. Wang et al., 2022). A study by (Rashid et al., 2018) aimed to compare children with functional hearing loss to those suspected of auditory processing disorder. The study highlighted the problems that these conditions might cause such as educational difficulties with spelling and handwriting while performing better in numeracy skills. These issues can also affect their attention and lead to language impairment ultimately impacting quality of life. A study that followed the early hearing deprivation significantly affects the development of hearing, language, and vision, particularly in infants with congenital severe sensorineural hearing loss (CSSHL). A study by Li et al., (2019) compared 34 infants with CSSHL to 20 infants. The results revealed that infants with CSSHL exhibited decreased brain activity in auditory and language-related regions indicating that hearing loss disrupts the functional connectivity between these areas. The disruption negatively impacts language acquisition and comprehension. As the duration of hearing loss increased, certain brain areas showed compensatory increases in activity, however the lack of auditory input led to poor recoverability of auditory and language functions. Therefore, cochlear implantation before 24 months can help to delay it resulting in less effective habilitation of hearing and speech due to the brain's reorganization over time.

Regarding the conditions volunteers must meet for the results to remain valid and comparable, factors such as sleep (F. Wang et al., 2024)(Al-Khalil et al., 2024) . The consumption of more than the accepted as healthy amount of coffee (between 3 to 4

cups a day) (Cano-Marquina et al., 2013) although coffee can enhance attention and focus it may impact negatively on cardiovascular health. Another factor to take in consideration is the number of alcoholic drinks (De Lorimier, 2000) consumed per day, stated that moderate intake is defined as 2-4 drinks for men and 1-2 for women. Excessive alcohol consumption can impair cognitive functions leading to decreased attention and poor comprehension. Additionally, it is needed to ask if the person is under the influence of psychotropic substance (Cecinato et al., 2013) has they can disrupt writing skill not taking in account all the health problems that follow those types of consumptions. On the other hand, stimulant medications used for ADHD can enhance attention and focus, improving comprehension and writing skills (Dokkedal-Silva et al., 2024).

2. Methods and materials

For population selection it was needed to implement exclusion criteria which includes people with any type of diagnosed neurological pathologies, attention deficits, eye and auditory pathologies (or being portable of a cochlear implant) since these are audiovisual tasks. The volunteer must not be under the effect of alcohol or psychotropic substances. Since it is intended to utilize an EMG, the subject cannot possess an upper limb prosthesis.

Before any test, a consent form (Annex I) which explained to the participant how the experiment would develop from entering the room until the participant leaves. If the participant was willing to enroll in the study, he would be asked to sign the consent form, and the next step was to answer three questionnaires. The first one being an Edinburgh Handedness Inventory (Espírito Santo et al., 2017; Espírito-Santo et al., 2017) (Annex II) which assesses the participant's dominant hand. The participant was provided with all necessary equipment to answer this questionnaire accurately. Next the volunteer completed a bilingualism questionnaire (Annex III), developed by L. Almeida, (2024), a Portuguese version of a bilingualism questionnaire (Tuller, 2015). Finally, the participant answered a socio-demographic questionnaire (Annex IV), also created by the student, which gathered information about the individual's background and health status and identify any potential issues that could affect the testing or make the results non-comparable with others.

During the volunteer's response to the questions, all necessary equipment for the testing process will be prepared and set up. This begins with activating the EEG Brain Vision ActiCHamp Plus device for synchronized signal acquisition and the Brain Vision Recorder and Analyzer software will also be launched to display and process the signals.

The human brain is divided into lobes, each with specialized functions. The frontal lobe, located at the front, governs cognitive processes like reasoning, decision-making, and voluntary movement, as well as personality and speech production. Behind it, the parietal lobe processes sensory information, spatial awareness, and orientation. The temporal lobe, near the temples, handles auditory processing, language comprehension, memory formation, and emotional regulation. At the back, the occipital

lobe is dedicated to vision, interpreting visual stimuli like color, shape, and motion. These interconnected lobes work together to produce thought, perception, and action.

Electrodes will then be placed in the EEG cap according to the 10-20 International System (Figure 1), ensuring comprehensive monitoring of the brain. While the entire brain activity is recorded, particular attention is given to the left hemisphere, where linguistic characteristics are most prominent. A total of 32 (EMG + 31 channels) channels will be used. The ground electrode, located on the volunteer's forehead, will be prepared first with conductive gel, followed by the remaining electrodes also with conductive gel. Key areas covered include the occipital, temporal, frontal, and sensorimotor regions, which are critical for detecting conditions related to handwriting, such as Parkinson's Disease and Dystonia.

In parallel, three EMG electrodes will be placed: two on the volunteer's extensor carpi ulnaris (forearm muscle) and one on the ulnar styloid, serving as a reference. This setup facilitates analysis the electrical potentials of the muscles and therefore an extrapolation of hand movement during the task.

A smartpen (Echo Pen Livescribe) will be used to record writing data. The pen operates independently through its software and activates when the participant presses the start button on the notebook that it is also given. It records event-related potentials, such as pen-down and pen-up moments, to capture any challenges the participant experiences while writing.

2.1. Tasks

Each test session will last 40 minutes in total, divided into two 20-minute segments: one for tasks in Portuguese (the main language) and the other for tasks in English (the second language) both for the subject's dominant hand. Each segment includes training and testing phases for better organization and comparison of results.

The test is divided into three tasks: task 1 - the participant is shown figures in a video and must replicate them in a notebook. This task starts with a training phase, followed by the test phase; task 2 - focused on pseudowords and has two categories: 2f (Phonological Task) and 2m (Morphological Task) where the participant will hear a pseudoword twice – 2 seconds – and write it down using the dominant hand. Both categories include a training phase followed by a test phase; task 3 - participants will

write real words in Portuguese for the Portuguese test and in English for the English test.

During each task, stimuli are presented in a video format. For each word or pseudoword, the video plays the audio for two seconds, followed by a five-second period where a blue screen is displayed. During this time, the participant writes the word in the notebook. A brief interval is included between each word to stabilize the signals being collected. This allows for better signal quality, improved detection of event-related potentials (ERPs), and alignment of the data with the task timing. After the test, the cap and the electrodes will be carefully removed. The cap will be rinsed with warm water and the gel on the electrodes will be gently removed using a toothbrush soaked in water. The volunteer will be provided a towel and access to the balneary to help remove any remaining conductive gel from their hair. All test details will be documented for later analysis, and preparations for the next volunteer will begin

2.2. Linguistic materials

The stimuli used in these tasks include symbols, pseudowords and real words, which are associated with linguistic, orthographic and psychomotor dimensions (Caetano Alves & Carvoeiro, 2019) as seen on table 1, 2 and 3 for Portuguese and English tasks, respectively.

Table 1 Task 1 - Symbols

Task 1 Symbols					
Training			Test		
O	П	C	L	W	K

Table 2 Words and pseudowords for Portuguese language tasks

	Training		Test			
Task 2f	Azito /asito	Gasmia	Paco	Irrês/Irrez	Xaropeiro	Guislerta
			Firo	Záguena	Extimão	Ilufonteido
Task 2m	Rujico/ Rugjco	Istradosa / Istradoza	Amorsimo	Solidância	Fugidoso	Zombemento
			Extremor	Mordãs	Chupagem	Gordéu
Task 3	Loja	Sobrancelhas	Pão	Harpa	Carteiro	Oxigénio
			Cara	Órgão	Sardinha	Higiene

Table 3 Words and pseudowords for English language tasks

	Training		Test			
Task 2f	Tico / Tiko	Thinpelow	Sali	Guitopa	Tulskan	Klupster
			Nefito	Celibaw	Plicrew	Xabolthic
Task 2m	Unbaby	Happition	Dogize	Knifely	Preisland	Chrystable
			Sunful	Doubtish	Disconceive	Biscuitment
Task 3	Body	Chocolate	Tomato	Yellow	Cinnamon	Vegetable
			Banana	Happy	Pharmacy	Orchestra

These words are designed to examine various aspects: phonological, morphosyntactical and semantical at linguistic level; form, size, length, direction, and pressure at the psychomotor level; and regularities and irregularities at the orthographic level and so *PEACE* (Carvoeiro, 2017) was developed. An instrument based on a holistic view of the neurophysiological processing of writing. It uses research methods such as literature review, thematic analysis, and focus groups consisting of 14 assessments. These assessments begin with basic tasks such as handwriting and letter writing and progress to more complex tasks like sentence and text writing. The assessment methods include copy, dictation, aiming to provide a comprehensive evaluation of written production.

2.2.1. Phonological, morphological and lexical dimension

The phonological dimension involves the manipulation of phonemic features, syllable structures, and word complexity. The morphological dimension addresses the selection of words with different morphological structures, such as monomorphemic versus polymorphemic words (Ardanouy et al., 2024). In terms of lexical variables, both familiar and unfamiliar words, as well as pseudowords, were included in the stimuli. This design allows for an in-depth examination of lexical processing, while controlling for familiarity effects (Chen & Durrant, 2024). By carefully controlling these linguistic variables, the study ensures a comprehensive approach to exploring the relationships between language processing and psychomotor performance in writing tasks.

2.3. Morphological and phonological dimension

To explore these cross-linguistic differences, the proposed experimental setup is designed to examine how individuals process, focusing on both phonological and morphological dimensions. The linguistic variables of the stimuli, particularly their phonological properties, as evidence suggests that these features significantly influence writing. For instance, studies such as Alves, (2012) indicate that phonological segmental properties impact writing, especially for words with varying degrees of linguistic complexities. This effect is often explored through tasks involving both words and pseudowords, highlighting the role of phonological properties in language processing. While these are completed, the EEG equipment will be prepared to record neural signals during writing tasks. By combining EEG with writing tasks it enables investigate how lexical processing differences observed across languages manifest at both cognitive and neurophysiological levels, providing insights into the brain's adaptability in accommodating the specific demands of different writing systems (Ziegler & Goswami, 2005) Speech perception relies on the integration of auditory and visual information, as illustrated by the McGurk Effect, where visual cues can alter auditory perception, while this study does not directly examine such bimodal effects, it is important to note that auditory perception is often influenced by visual input, especially with less familiar stimuli like pseudowords. Thus, in writing tasks based solely on the auditory channel, linguistic properties, particularly phonological ones, play a significant role (Barone et al., 2016; Collignon et al., 2008).

2.4. Smart Pen

To study handwriting within a population, the usage of a Smart Pen is essential, as it enables dynamic analysis by capturing the start and the end of each stroke. These analyses can lead to a better understanding hand movements and familiarity with what is being written, or even the identification of any type of neural pathology within the study groups, as individuals with neurodevelopmental disabilities require more time than the control group for on-paper and in-air stroke activities (Fogel et al., 2019). A study by (Kawa et al., 2017) where it was used a Livescribe Echo Pen with the purpose to develop a diagnostic tool based on handwriting and well commented for note taking and text-to-speech software (O'Sullivan, 2018); these type of pens function as a

traditional ballpoint pen, however it digitize each pen stroke written, after each task a USB cable is used to download the data to the computer (Stahovich et al., 2019).

The smart pen and notebook were used as a tool for the subject to write with and on during task as it will help monitoring time strokes, handwriting and harmony of each word. The smart pen will start recording once the button “Start” on the notebook is pressed with it.

2.5. EEG data processing

Data from 32 channels (AF7, AF3, AF4, AF8, AFz, C1, C2, C5, C6, CP3, CP4, CPz, F1, F2, F5, F6, FC3, FC4, FT7, FT8, P1, P2, P5, P6, PO3, PO4, PO7, PO8, POz, TP7, TP8 and EMG) were analyzed using EEGLAB running on MATLAB®. EEG signals were first re-referenced to the average of all scalp electrodes and then subjected to an independent component analysis (ICA) tool and the muscle artefacts from the dataset were removed, and the EMG channel was set aside to facilitate the study of the EEG data, ending up with 31 channels.

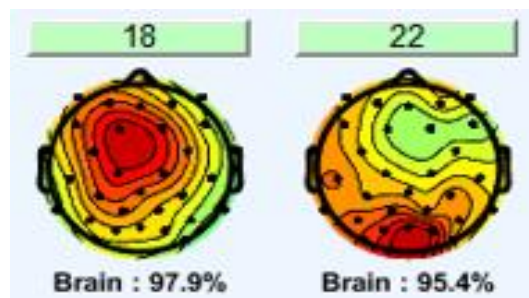


Figure 2 Results with 95% or higher of brain value

The dataset was then conducted on the delta (0.4 – 4), theta (4 – 8), alpha (8 – 13) and beta-gamma (13 - 50) frequencies bands, that are studied as a whole due to cross-frequencies effects (Dos Anjos et al., 2024) and their relevance for the study of cognitive, linguistic and sensorimotor processes. The analysis proceeded with an Independent Component Analysis (ICA) labeling process to examine brain activity during the tasks. By shortening the time intervals, this approach enabled a more precise examination of brain activity specifically during the word-writing process. Attention was then directed to the images displaying brain activity at or above 95%, as shown in Figure 2.

3. Results and Discussion

This chapter presents the findings of the study, integrating data analysis with an in-depth discussion to interpret the results in the context of the research objectives.

3.1. EEG Results

Firstly, resorting to EEGLAB function “plot data” and “channel locations” we started to identify which channel number corresponds to which channel name as depicted in figure 3, as AF1 is associated to channel 1, for example.

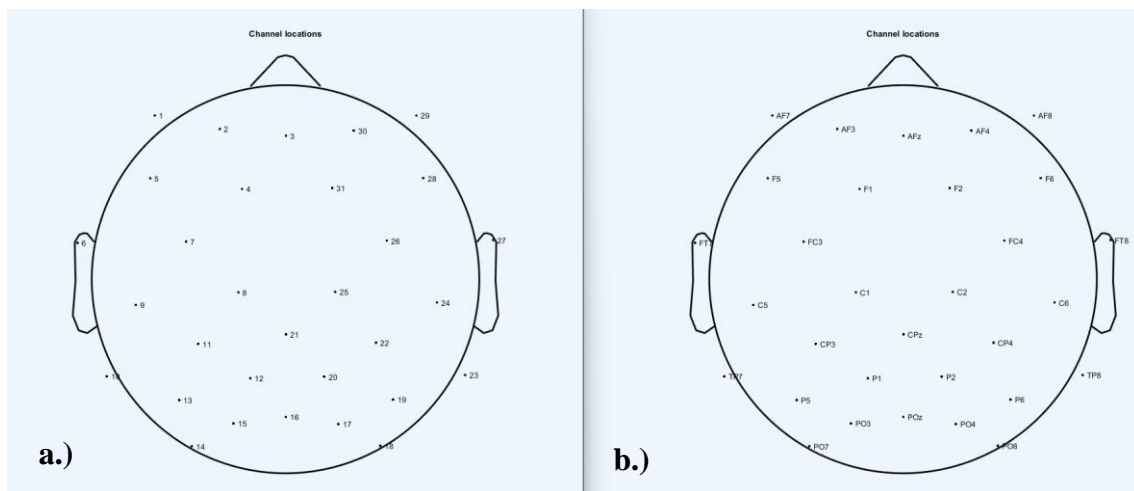


Figure 3 Channels location by number a.) and by name b.).

3.1.1. Frequency Analysis

The human brain operates through a complex network of electrical activity, and this activity can be measured using an electroencephalogram (EEG). EEG captures brain wave patterns that reflect various states of consciousness, cognitive processes, and emotional states. These brain waves are categorized into different frequency bands based on their rate of oscillation, each of which is associated with specific mental states or functions.

The EEG frequency bands that will be studied are delta waves (0.5 to 4 Hz), theta waves (4 to 8 Hz), alpha waves (8 to 12 Hz), beta waves (12 to 30 Hz) and gamma waves (30 to 100 Hz).

These frequency bands are not isolated from one another; rather, they interact dynamically throughout the day, often shifting depending on a person's activities, mental state, and level of attention or relaxation. EEG provides a valuable tool for

studying brain function, diagnosing neurological disorders, and even exploring altered states of consciousness in research settings. Understanding these frequency bands can offer insights into both the brain's normal functions and its response to various stimuli or conditions.

3.1.1.1. Beta/Gamma Waves

During the analysis there were clear muscle artefacts involved during the data collection mostly captured by the beta/gamma frequencies (Whitham et al., 2008), results due to muscle movement from open and closing the eyelid, blinks, by frowning and by facial muscles, resulting in those values amongst the heartbeat and others, shown in figure 5.

The presence of EMG activity can lead to electromagnetic interference across a range of EEG frequencies. Muscle movements, particularly those involving facial or other voluntary muscle activity, generate electrical signals that can overlap with brainwave frequencies in multiple ranges, from low to high frequencies. These signals can distort EEG recordings by creating artifacts, making it challenging to isolate neural activity from the interference caused by muscle activity. (Q. Chen et al., 2025a), figure 4. As shown in figure 5, it is possible to observe the noise made near the 1998 milliseconds where the individual could be waiting to hear the word for the second time as or simply trying to keep focus which could cause frowning or any type of mouth/lips movement (Whitham et al., 2007).

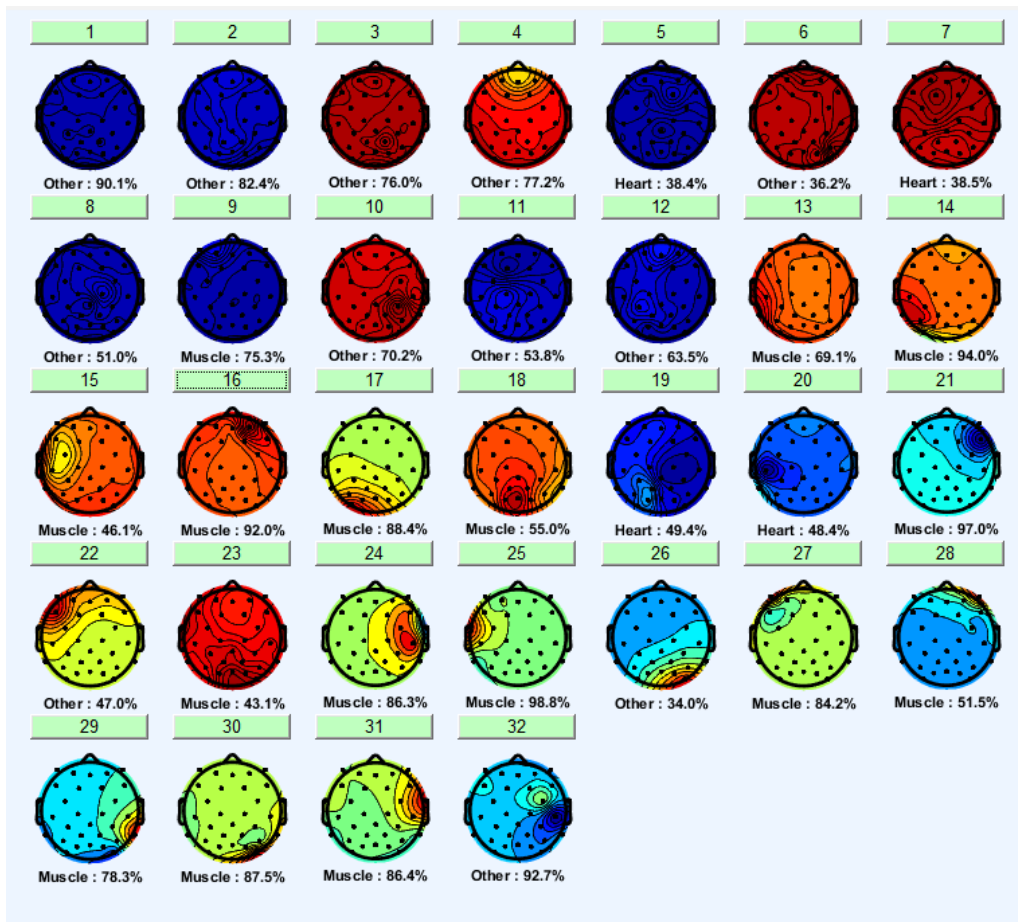


Figure 4 EEGLAB results for beta/gamma frequencies during morphological task (2m_training)

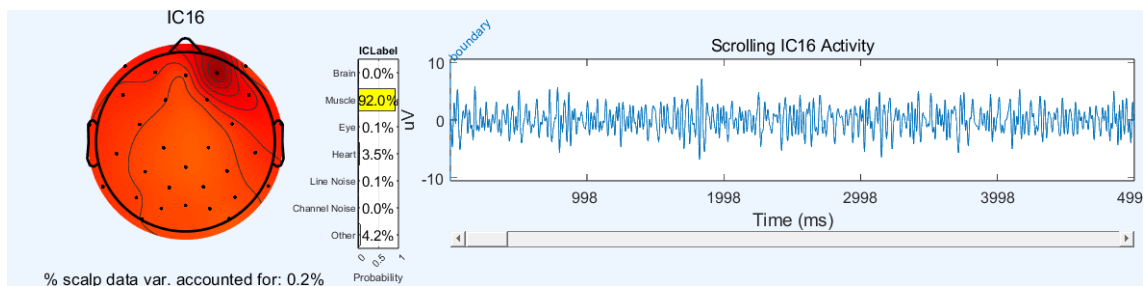


Figure 5 Muscle percentage on IC 16

With this data, we can see that at these frequencies everything associated with physiological movements is detected and thus hinders the capture of brain activity.

3.1.1.2. Delta Waves

The dataset was cleaned within the 0.5 to 4 Hz frequency range, also known as the delta frequencies (Miraglia et al., 2021), these frequencies are typically observed during states of rest and sleep, depending on the brain's state (Molae-Ardekani et al., 2010), and are also associated with memory consolidation.

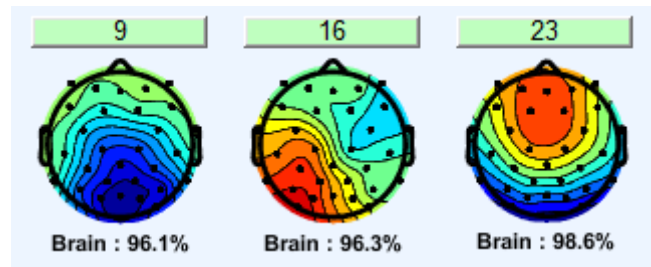


Figure 6 Brain values of IC 9, IC 16 and IC 23 during delta waves extraction

During the data analysis, a pattern emerged linking delta waves to individual components, with the channels on parieto-occipital and anterior-frontal regions, showing the strongest values, corresponding to ICA components 9, 16, and 23, respectively, shown on Figure 6. Component 9 indicates that there is a higher activity in the anterior-frontal region depicted with green coloration, indicating its involvement in cognitive functions such as attention and motor planning. The prefrontal cortex plays a central role in tasks that require executive control, the ability to shift attention, and decision-making. These functions are essential for tasks involving motor actions and sensory processing, such as writing. The neural activity of Component 9 aligns with attentional reorientation, further suggesting its contribution to cognitive processes that govern attention shifts during task execution.

The frontal areas are key for attention shifting and motor execution, while the gradual activity extension towards the back suggests the integration of sensory inputs with motor feedback. This pattern implies that Component 23 helps mediate the shift from cognitive control to sensorimotor processing, especially in tasks requiring attention to auditory stimuli, such as language processing.

Component 16 exhibits red coloring in the parieto-occipital region, which is typically associated with visual processing and spatial awareness. This region is essential for the integration of visual stimuli and the coordination of sensory-motor functions, particularly when tasks involve visual-spatial attention and writing-related processing.

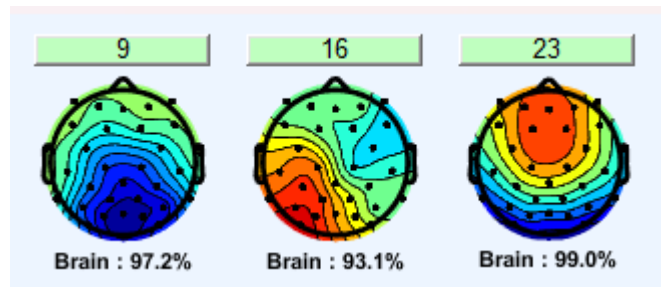


Figure 7 Brain values of IC9, IC16 and IC23 during delta waves extraction during writing

Furthermore, the activity shown in Figure 7 indicates that Channel POz, located in the parieto-occipital region, exhibits reduced activity during the writing task compared to earlier stages. This decrease in activity suggests that the brain reallocates resources to facilitate visual reorientation and motor coordination, processes that are crucial for integrating visual input and managing the fine motor control needed for writing. This change in brain activity underscores the dynamic relationship between attentional focus and motor execution during complex tasks.

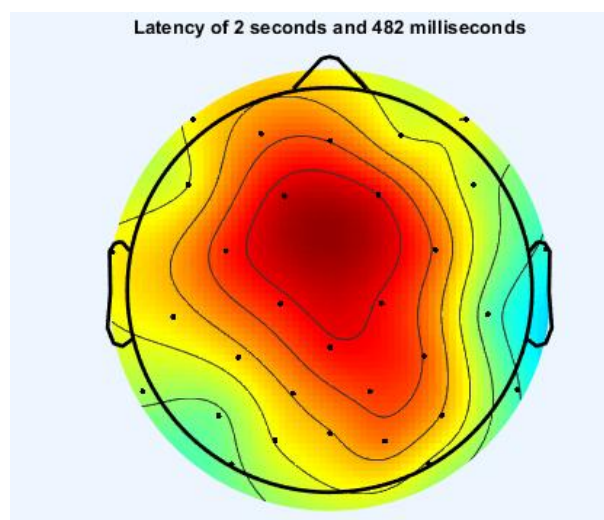


Figure 8 Brain activity 2 second and 482 milliseconds - writing a word

During the writing task, while the primary components exhibit the most significant delta wave activity, broader patterns of neural engagement are evident. As shown in Figure 8 distinct spikes in activity around 2482 milliseconds, coinciding with the act of writing. These spikes suggest the activation of regions responsible for fine motor coordination, attention shifts, and potential responses to external stimuli.

Channels F1 and F2, associated with motor planning and execution, demonstrate activity likely linked to the cognitive process of deciding the next letter to write or

evaluating the progress of the word. These areas are critical for planning and coordinating the precise hand movements required for writing. Meanwhile, channels C1 and C2, connected to sensorimotor integration, exhibit activity that may reflect adjustments in hand positioning, changes in grip, or error correction. Together, these observations underline the dynamic interplay between motor control, attention, and sensory feedback during the complex task of writing.

3.1.1.3. Theta Waves

The next frequency band to be analyzed was the theta waves, which occur in the 4-8 Hz range (Y. Li et al., 2024) and are typically associated with problem-solving tasks and transitions between wakefulness and relaxation. Regarding the results for the phonological (2f), morphological (2m), and Portuguese (3) tasks, there are notable differences in the channels with the highest levels of activity. For the pseudoword tasks, the majority of the brain activity is concentrated on the right hemisphere, with a few exceptions. In contrast, during the task involving Portuguese words, additional channels are activated on the left hemisphere, as shown in Table 4.

Table 4 Number of channels in each task during writing

		IC
Pseudowords	Task 2f	21 26
	Task 2m	20 24 25 29 30
Portuguese	Task 3	9 12 23 25 27 31

These results likely reflect the higher cognitive demands of meaningful words compared to non-meaningful pseudowords (X. Chen & Zhang, 2025; Vergara-Martínez et al., 2021). As for the phonological tasks channels located in the parieto-occipital region, caused by IC 21, TP8 which is the channel covered by IC26. The parieto-occipital region and Channel TP8 are critical for phonological tasks as they are involved in processing the structure of words, particularly by segmenting and decoding phonemes—the basic units of sound in language. These brain regions assist in handling abstract sound structures, which are foundational in tasks such as recognizing speech sounds and processing auditory stimuli. In phonological tasks, these regions are

engaged in breaking down the auditory input into simpler components, facilitating the decoding of sounds into comprehensible linguistic forms.

The parieto-occipital region contributes to the integration of auditory and spatial information, supporting the identification and processing of phonemes. Channel TP8, located at the temporal-parietal junction, plays an essential role in combining auditory signals with phonological representations, which is crucial for tasks that involve distinguishing and manipulating speech sounds. This is particularly important for understanding and processing phoneme segmentation, where the brain isolates individual sounds within spoken language.

In morphological tasks, which require the breakdown of words into their constituent stems and affixes, additional cognitive processes are engaged. The anterior frontal regions, which are linked to higher cognitive functions such as attention and working memory, support the mental manipulation of these structures. For instance, Channels C1 and C2, located over the sensorimotor cortex and associated with processing motor functions, show activation related to these tasks. These channels are involved in the cognitive load required to mentally segment and manipulate morphemes while also supporting attention and memory functions that manage the complexity of language tasks. This highlights the interplay between the brain's motor regions and cognitive control processes, facilitating the decomposition of words and the handling of linguistic complexity, shown on Figure 9.

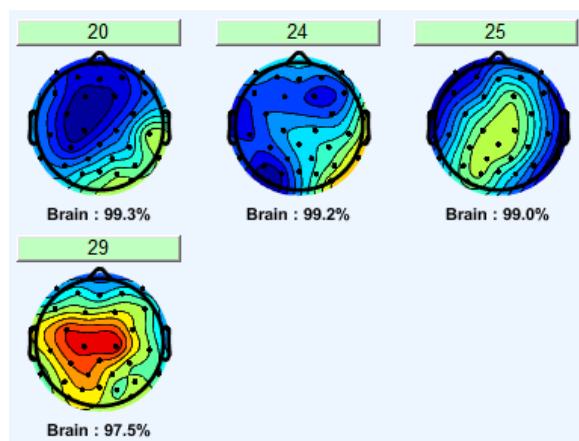


Figure 9 Brain values of IC20, IC24 and IC25 and IC29 during writing - morphological task

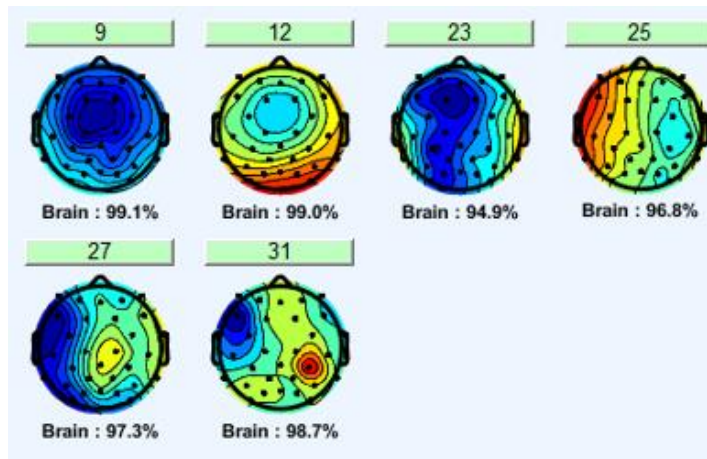


Figure 10 Brain values during writing - Portuguese task

On the other hand, for the Portuguese task, there is an immense involvement of channels CP4, shown on figure 10, together with the antero-frontal region and the channel FT7, as they are activated during the processing of real words, which requires active recall, semantic retrieval, and phonological processing (Dang et al., 2019). Unlike tasks involving pseudowords, which demand more localized activation focused on phonological structure and less on meaning, these channels reflect the integration of motor, semantic, and auditory components essential for understanding real words.

3.1.1.4. Alpha Waves

Regarding alpha waves, these are the frequency range where it was reported the most number of channels with a brain activity, figure 11, equal or higher than 95% in each task since these are considered the brain's default rhythm representing a state of idle yet alert processing which makes the individual able to switch to task-related activities (Hussin & Sudirman, 2013b).

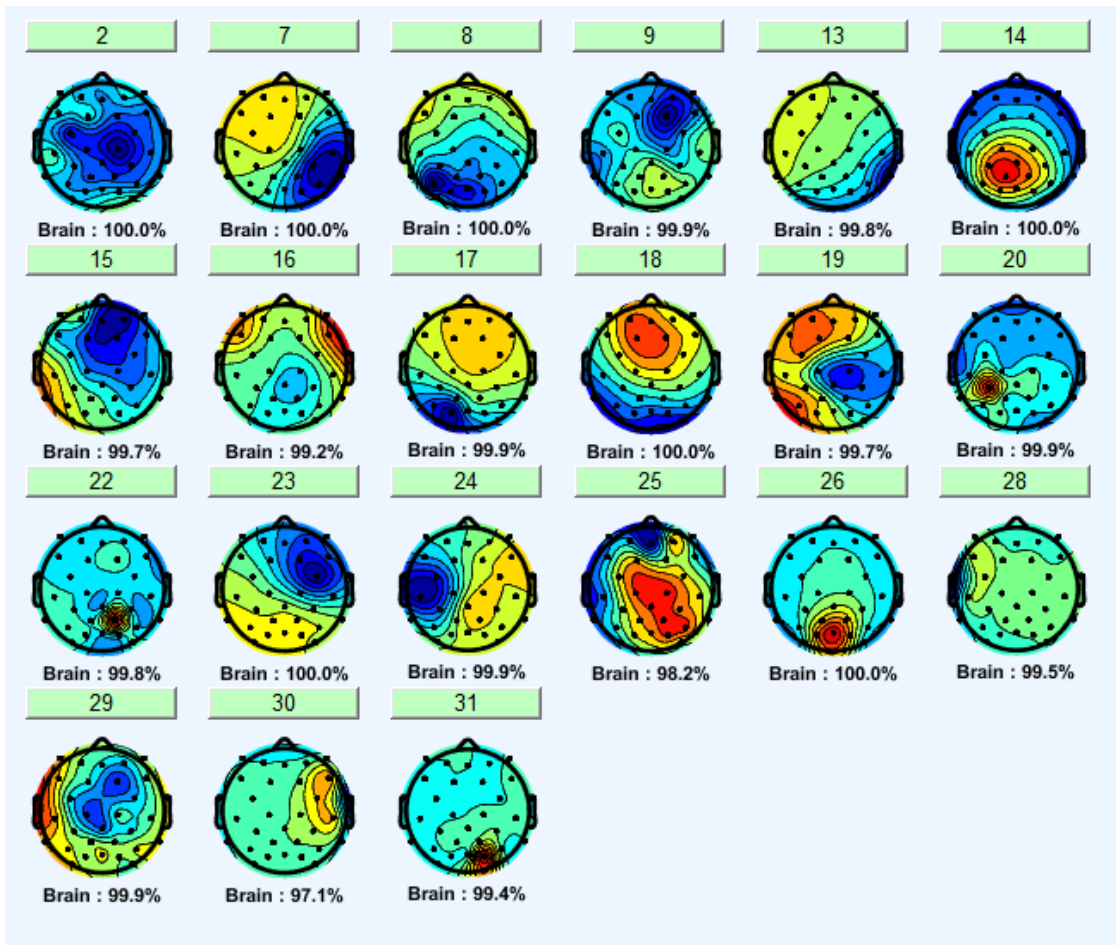


Figure 11 Channels with a brain activity equal or higher than 95% extracted of alpha waves from task 2f training

The results depicted in figure 11 illustrate the correlation between centro-parietal, anterior-frontal, parieto-occipital and temporal lobes during writing tasks with dominant-hand. The correlation between the centro-parietal, anterior-frontal, parieto-occipital, and temporal lobes during writing tasks highlights the interconnected nature of cognitive and motor processes essential for this complex activity. The centro-parietal regions are involved in motor control and sensory processing, particularly aiding in the fine motor coordination needed for writing. These areas help translate cognitive intent into physical action by managing the movement of the hand and fingers during the task.

The anterior-frontal regions, particularly the prefrontal cortex, support higher cognitive functions like attention, working memory, and decision-making. These regions help plan the writing task, maintain focus, and adjust the process as needed, ensuring that the written output aligns with cognitive goals. Meanwhile, the parieto-occipital regions are key for spatial processing and visual integration, allowing individuals to orient and align written words on the page. These regions help the brain

maintain spatial awareness and adjust writing movements based on visual feedback. The temporal lobes are crucial for language processing, encompassing both phonological and semantic systems. These regions contribute to word retrieval, grammar, and the overall structure of written language, linking written symbols with their meanings and sounds.

Together, these brain areas collaborate to facilitate the smooth execution of writing tasks, as they process both the sensory input (visual feedback), and the motor actions required to produce written language. This coordination demonstrates the integration of various brain regions to perform a task that combines cognitive planning, language processing, and motor execution.

3.1.2. Independent Component Analysis

Independent Component Analysis (ICA) is a computational method used to separate a multivariate signal into independent components, making it a powerful tool in signal processing and data analysis. ICA aims to disentangle mixed signals by identifying the underlying sources that contribute to the observed data. This technique is particularly valuable in fields such as neuroscience, where it is often applied to analyze brain imaging data like EEG, isolating neural signals from noise or artifacts. By leveraging assumptions about the statistical independence of source signals, ICA enables researchers to uncover meaningful patterns and gain insights into complex systems. In EEG analysis, ICA works with data collected from multiple electrodes, for example, 31 electrodes placed on the scalp these electrodes capture a mixture of signals from various sources, including brain activity, muscle signals such as EMG characterized by high-energy frequencies greater than 30 Hz, eye movements like electrooculogram that produce temporal signals due to horizontal and vertical saccades from the dipole effect of the eyes, heart activity seen in ECG, line noise such as 50/60 Hz interference, and channel noise.

To separate these components, ICA utilizes several parameters such as the topology of the electrodes, spectral density, signal power, and autocorrelation. The result of ICA is a measure of the likelihood that a particular source is present in each channel. A likelihood above 95% is considered relevant. This threshold is commonly used as a standard to determine significant components, although the specific justification for 95% often arises from statistical confidence intervals and empirical

practices. ICA often focuses on components with higher signal strength, which may depend on the specific frequency range being analyzed by identifying these dominant signals, ICA helps distinguish meaningful sources, such as brain activity, from noise or artifacts, enabling more accurate and reliable analysis.

3.1.2.1. Beta/Gamma Waves

IC 30 for beta and gamma waves presenting a 99,5% of muscle activity, since we cannot see brain activity, as shown in Figure 12, thus it is important to retain that independent components have a spike of activity at specific times, while writing therefore being noise during 1998 milliseconds shown in Figure 5, as well.

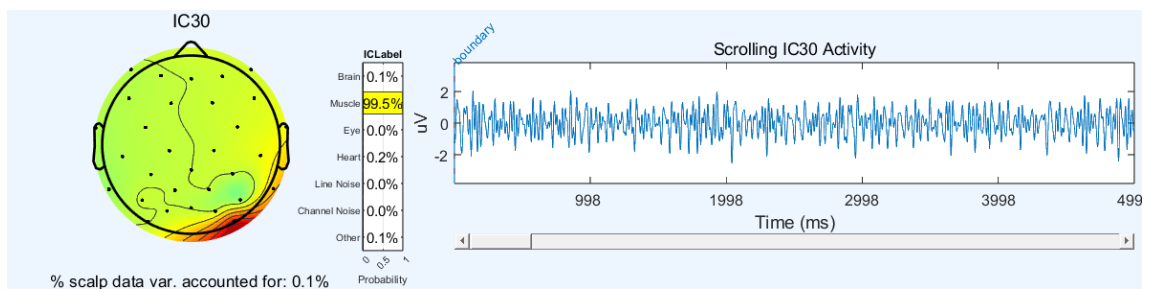


Figure 12 Label for the independent component 30

3.1.2.2. Delta waves

In the delta waves range three IC show a brain activity with equal or higher than 95%, being the highest one IC 23, shown in Figure 13, with a spike during the writing task at the same time, 1998 ms.

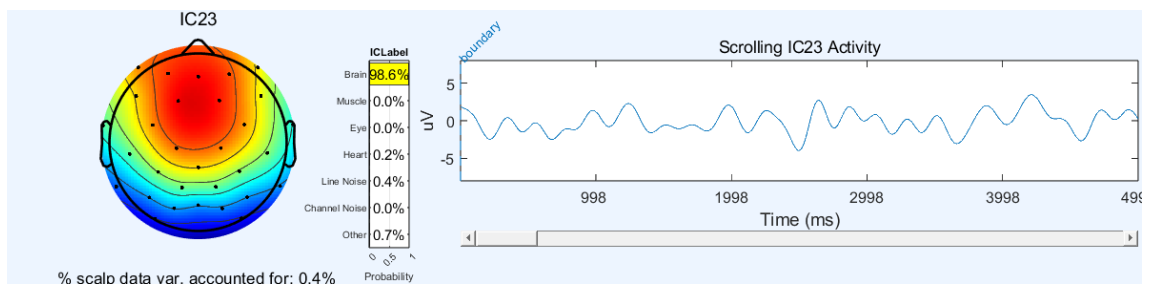


Figure 13 Label for IC 23

3.1.2.3. Theta waves

For theta waves, the same happens as the IC with the highest activity changes, however it is possible to analyze a concordance with delta waves where the area anterior-frontal provides the greatest intensity.

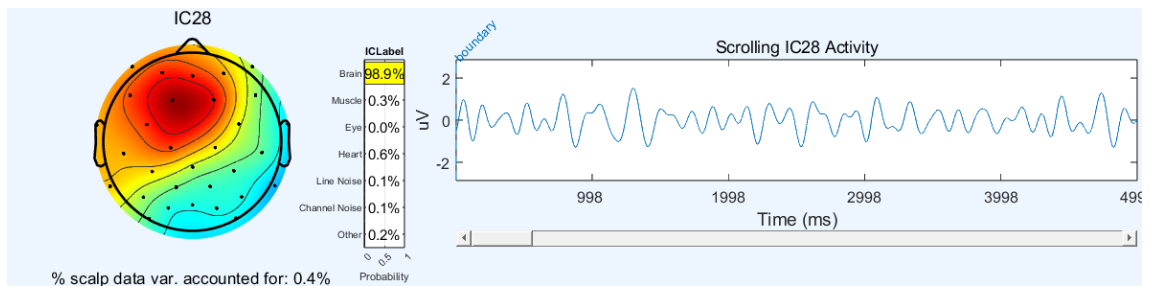


Figure 14 Label for IC 28

3.1.2.4. Alpha waves

Lastly, the alpha waves provide the highest number of IC with brain activity equal or over 95%. In figure 15, IC 4 enables a visualization of a brain activity on the occipital region of the brain. Figure 15 also presents spikes of intensity at the same time, 1998 milliseconds.

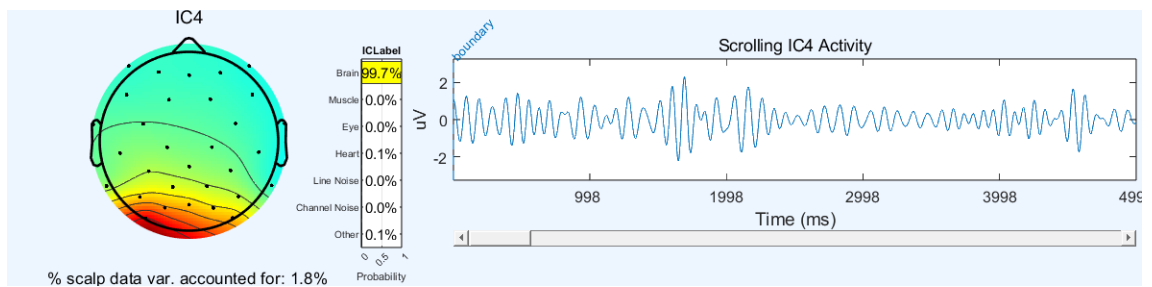


Figure 15 IC 4 Label

3.2. Language Results

Here, the results related to language processing are discussed. This includes the phonological, morphological, and lexical aspects that were examined in the tasks. The findings are contextualized within the broader literature on language processing.

3.2.1. Symbols Task

In this section, the bilingual participant was instructed to replicate a symbol displayed on the screen. The results, presented in Figure 16, reveal the ICs with high brain activity, which are different for each symbol as shown in Table 5. These regions include those associated with visual processing IC 30 making usage of the occipital region, as shown in figure 13, for motor planning and sustained attention anterior-frontal region – IC 27. The channels primarily located in the right hemisphere correspond to the cognitive and motor functions engaged during the task. It is important

to note that differences in symbol complexity may influence the observed brain activity, as the electrode maps for the first and second symbols do not activate the same neural regions.

Table 5 Comparison between Symbol 1 and 2 for IC

IC	Symbol 1	Symbol 2
11	✓	
18		✓
22	✓	
27	✓	✓
28	✓	✓
30	✓	✓

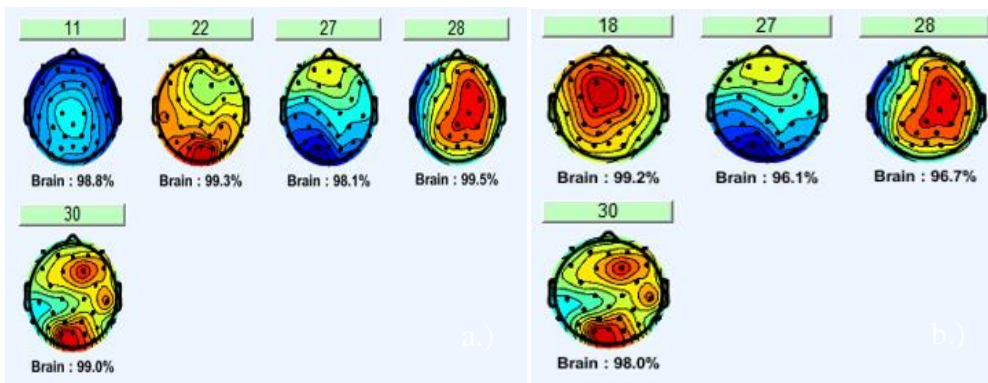


Figure 16 Comparison between brain activity of symbol 1, a.) and symbol 2, b.)

3.2.2. Training tasks phonological vs. morphological vs. Portuguese

When comparing all tasks that were purposed to the individual, it has been seen that the number of the channels with a brain activity equal or higher than 95% differ depending on which task and which word the subject is writing, not only in between tasks but also different words in the same one, Annex V and VI, respectively.

These differences can be related to the word itself since words can differ in terms of length, combined phonemes and the emphasis on different syllables; short, simple pseudowords tend to activate fewer channels as longer ones recruit additional regions for working memory and motor planning, this variability reflects the brain's dynamic approach to processing linguistic stimuli that serve the same functional purpose.

3.2.3. Test tasks phonological vs. morphological vs. Portuguese

The same can be seen when looking at Annex VII regarding 2m, 2f and Portuguese test tasks where and more meaningful words.

Since morphological tasks engage a broader range of cognitive and neural mechanisms that overlap between real and pseudowords where both words may activate

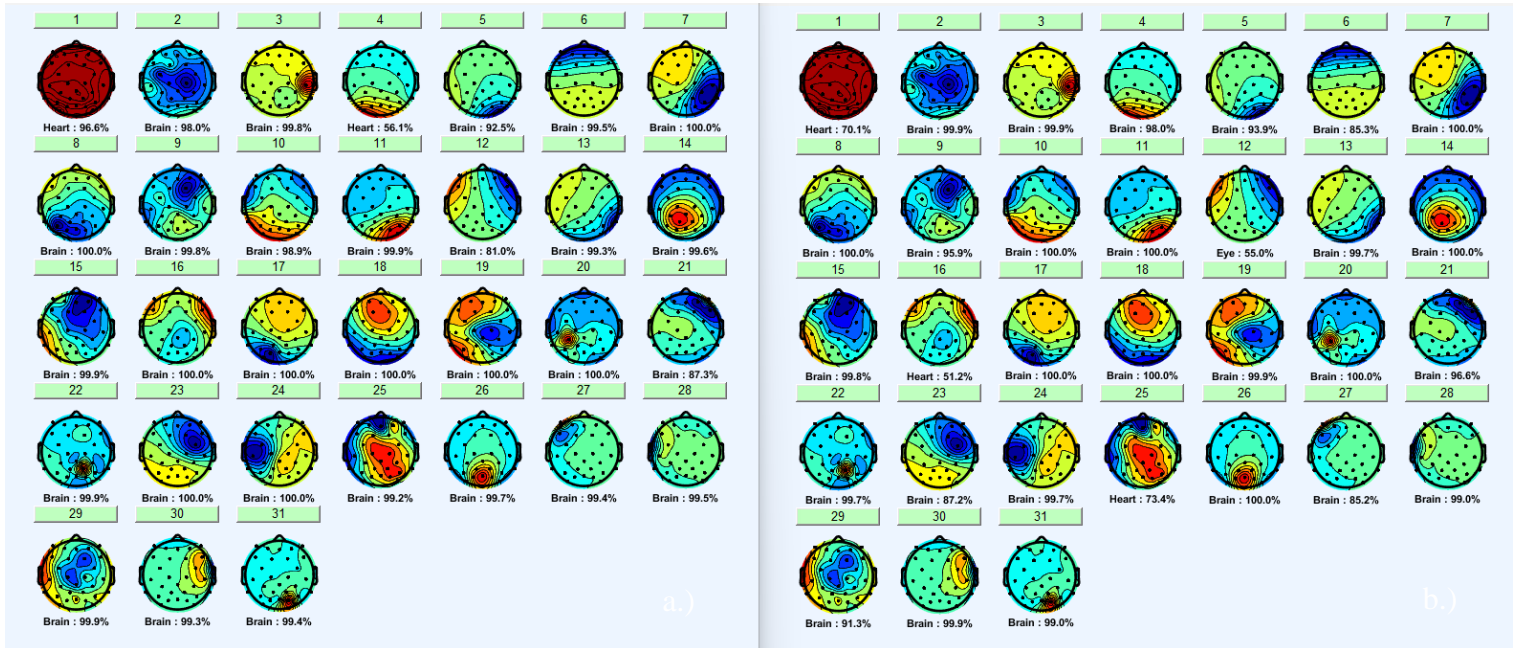


Figure 17 Data map of the components of the test 2m, a.), and test 3 - Portuguese, b.).

regions responsible for parsing morphemes (J. Wang et al., 2024) due to a recognizable feature within the written pseudoword, as it is suffix or prefix when compared to a real word, figure 17.

As figure 17 stands there can be seen that both maps are almost identical differing in the activity of certain channels that can be in word processing written above were Portuguese words need for example central and for decoding processing different from a real word from the Portuguese test.

3.2.4. Task phonological vs. morphological

When processing pseudowords, the brain tends to engage more areas related to morphological analysis compared to phonological processing. This is because morphological tasks require rule-based reasoning to decompose words into their constituent morphemes, a process that mimics the language's morphological structure. Pseudowords, designed to reflect the morphology of the target language, rely on

temporal regions for recognition and parietal regions for structural integration. Additionally, when pseudowords lack pre-existing lexical representations, the brain experiences an increased cognitive load due to the need to process and integrate novel linguistic forms. This heightened demand emphasizes the involvement of regions associated with higher-order cognitive functions, such as rule application and morphological analysis, and is consistent with the idea that the brain adapts to unfamiliar linguistic input by recruiting additional neural resources (Wang et al., 2024).

Phonological analysis mainly activates auditory and temporal brain regions for processing sound patterns. When memory or attention is required, frontal and parietal areas are also engaged. This highlights the brain's coordination of auditory recognition with cognitive functions, particularly for complex tasks demanding memory or attention resources.

3.2.5. Portuguese Vs. English Language

When comparing the number of channels recalled by the Portuguese words with the English during task 3 training (real words training task), shown on Table 6, ones since the neural networks are highly efficient and well-established, whereas the latter may engage with fewer channels due to weaker lexical and semantic and greater reliance on language control mechanisms.

Table 6 Comparison between tasks with word in Portuguese (native) and English (foreign) language

IC	English	Portuguese
1		
2	✓	✓
3		
4		
5		
6		
7	✓	✓
8	✓	✓
9		✓
10	✓	
11	✓	✓
12		
13		✓
14	✓	✓
15		

16		✓
17		✓
18	✓	✓
19		✓
20	✓	✓
21		✓
22		✓
23	✓	✓
24		✓
25		✓
26		✓
27		✓
28		
29		✓
30	✓	✓
31		

These results can depend on some factors as experience with the foreign language as a higher proficiency lead to an overlapping in neural networks which could increase the number of channels activated in the English words task; the differences of semantic and morphological processing as the foreign language has a less complex morphological system (Lee & Kim, 2025), however not implying less effort the brain tends to focus its resources on key regions.

The results highlight distinct neural activation patterns across phonological, morphological, and lexical processing for both Portuguese and English. Morphological tasks, particularly those involving pseudowords, engage a wider network of brain areas due to the need for rule-based analysis, as these tasks require decomposition of words into morphemes and mimic the structure of the language. This activation is often observed in temporal and parietal regions, which are crucial for recognition and structural integration of linguistic elements (Hertrich et al., 2020; Leminen et al., 2019). On the other hand, phonological processing, which is primarily concerned with sound patterns, is more localized to auditory and temporal regions (Davis et al., 2008).

Interestingly, the processing of Portuguese, a language with complex morphology, activates a larger number of brain regions compared to English. This is likely because the intricate morphological structure of Portuguese demands greater neural resources for processing and integration (Garbin et al., 2010). Conversely, English, with its relatively

simpler morphological system, places more demand on language control mechanisms, reflecting a different set of neural processes, often involving frontal and parietal regions for lexical retrieval and cognitive control (Bialystok et al., 2009).

These findings suggest that bilingualism and proficiency play a significant role in shaping neural processing efficiency. Proficient bilinguals may exhibit more streamlined and efficient neural processing due to enhanced cognitive control and language switching abilities, whereas less proficient individuals may show less optimized activation patterns across languages (Fabbro, 2001). Overall, this differential activation underscores the complexity of language processing in bilinguals and the impact of linguistic structure on neural efficiency.

3.3. Echo Desktop

Using the Echo Desktop software, the time taken by the volunteer to write each word with their dominant hand was recorded, along with their comfort level when writing pseudowords, Portuguese words, and English words. As shown in Figures 18 to 21, the volunteer took longer to begin writing pseudowords and English words compared to Portuguese words. This delay suggests that the volunteer may have experienced uncertainty regarding the structure and meaning of the non-native words, likely due to the familiarity and ease associated with their native language, Portuguese. The extended initiation time for pseudowords and English words may reflect challenges in processing unfamiliar or less familiar linguistic forms, as opposed to the more automatic processing of native language words.

Other important points which can lead to an extension of the writing time of the word are the reposition of the hand or arm or even to adjust the smart pen due to its weight causing a different stress resulting on more uncomfortable grip and a slightly more uneven handwriting of the word.

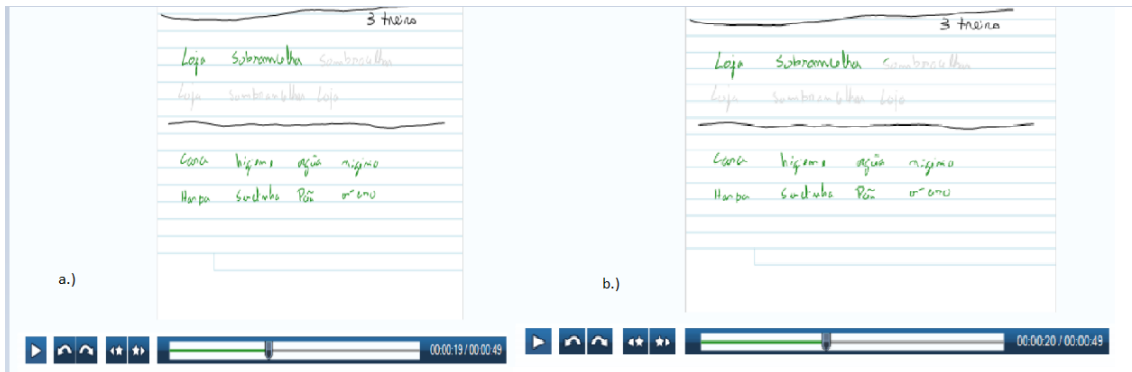


Figure 18 Time that the word "Sobrançelhas" was heard (19s) and started being written (20s)

Figure 18 where we can see the immediate response from hearing the word to start writing it and the time it took to finish it, figure 19.

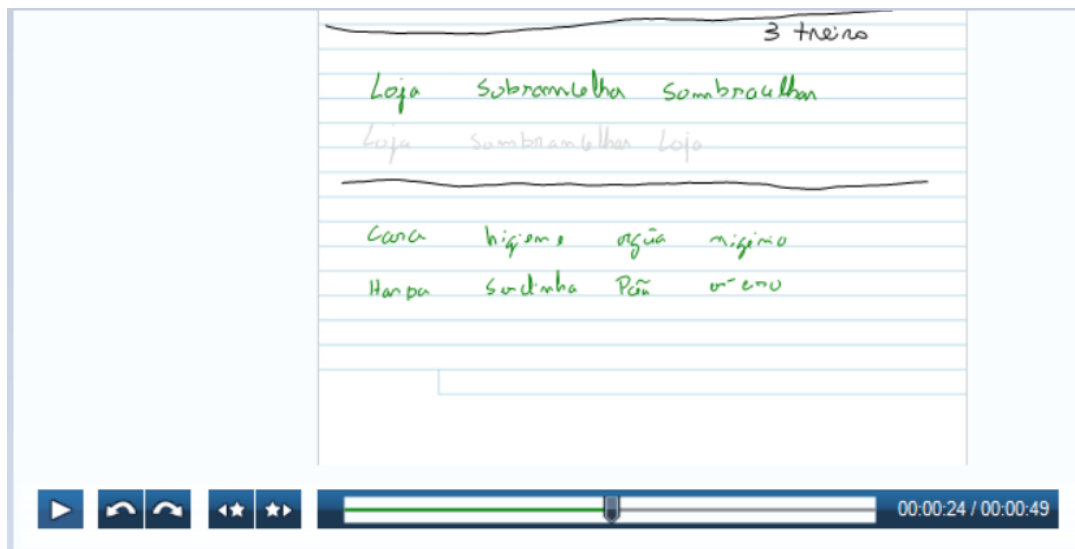


Figure 19 Time stamp at the word was stopped being written (24s) which took 4s to complete

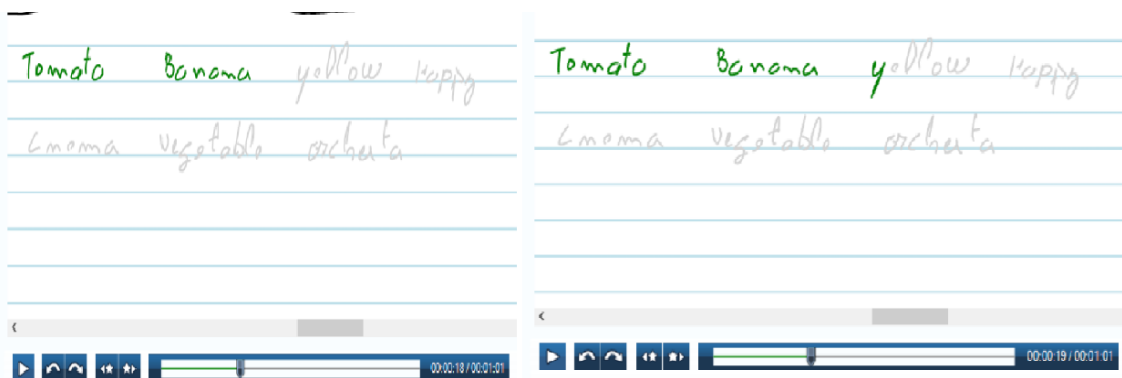


Figure 20 Time that the word "Yellow" was heard (18s) and started being written (19s)

Despite figure 20 showing a response time equal to the word in Portuguese it is important to notice that when the word started to be written the stroke was already fast trying to compensate a low time response to when it was heard.

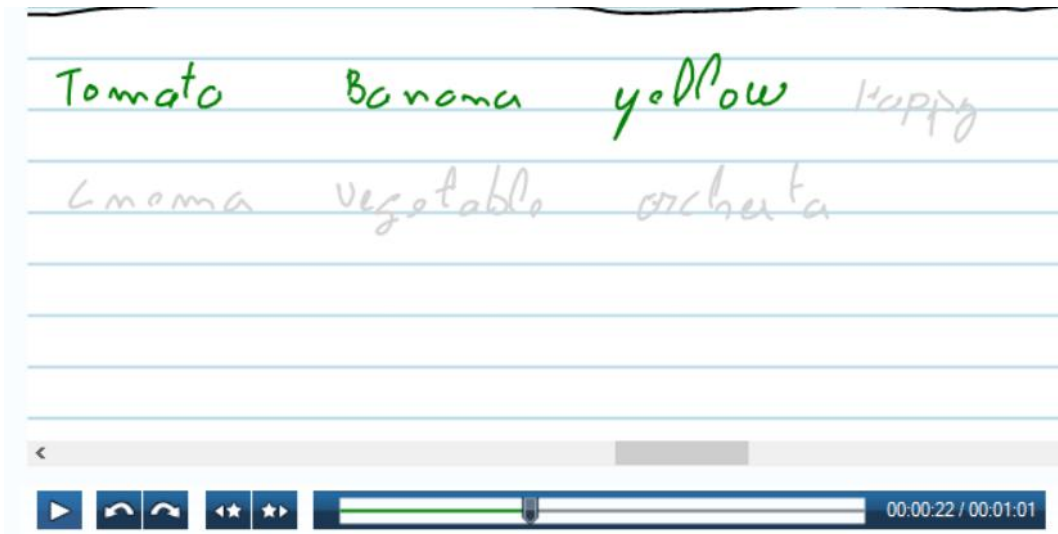


Figure 21 Time stamp at the word was stopped being written (22s) which took 3s to complete

The time difference that took to finish both words depends on the word itself also, since the word “Yellow” is shorter than the Portuguese word “Sobrancelhas”.

The results show that writing times were longer for pseudowords and English words compared to Portuguese, likely due to uncertainties in word structure and meaning. Physical factors, such as hand repositioning and adjusting the smart pen, also affected writing time and comfort. These findings emphasize the role of language familiarity and physical comfort in writing performance.

3.3.1. Statistical data

To understand the difference between writing Portuguese words and English words, and with the help of Echo Desktop, the time that each word has taken to write down shown in Annex VII, where the population is referring to the number of words to each language test.

$$M = \frac{\sum xi}{N}$$

$$\sigma = \sqrt{\frac{\sum(xi - \mu)^2}{N}}$$

Where: σ – is the standard deviation of the population, M – mean, x_i – each time that took for each word to be written, μ – mean of the population and N – the size of the population.

With this we can achieve a σ of 1.6E-16 seconds for the writing time of Portuguese words, compared to a 2.9E-16 seconds for English words. As Portuguese as the native language the brain can process the words and start the tasks faster then using words of a second language.

4. Final Remarks

The results from the EEG study provide insights into how the brain processes linguistic stimuli across different types of tasks. By utilizing EEGLAB to extract and analyze EEG data, significant observations were made about the neural activation patterns associated with beta/gamma, delta, theta, and alpha wave frequencies. These findings highlight the dynamic nature of the brain's response to phonological and morphological processing of pseudowords and Portuguese words.

By employing advanced methods to clean and separate these artifacts, we were able to isolate more accurate neural data the EEG data provided insights into the role of these brainwaves, demonstrating how they reflect different stages of cognitive processing during writing tasks. For instance, delta and theta waves were found to be particularly prominent during tasks involving cognitive control and fine motor coordination, underscoring the complex relationship between cognitive states and motor performance. These results align with the growing body of research suggesting that motor actions and cognitive processes are intricately linked during complex tasks such as writing.

In examining task-based differences, the study revealed important distinctions between how the brain processes real words and pseudowords. Real words, due to their semantic richness, involved more widespread activation across multiple brain regions, including those responsible for memory, semantic processing, and motor planning. In contrast, pseudoword processing appeared more localized to regions involved in phonological and morphological processing, which suggests that real words engage a broader and more intricate network of neural resources.

Another aspect of this study was the exploration of neural differences in language processing between native and non-native languages, which revealed that native language tasks activated a broader range of brain regions compared to non-native language tasks. This difference was particularly evident when participants engaged in writing tasks in their native language, where stronger neural activation was observed in areas responsible for higher-order cognitive functions such as memory retrieval and semantic processing. Conversely, non-native language tasks, although still engaging similar brain regions, showed less widespread activation, which may reflect the additional cognitive load associated with processing a second language.

The study also examined the influence of linguistic familiarity and task difficulty on writing performance, noting that participants took longer to initiate and complete writing tasks involving pseudowords or non-native language words. This delay can be attributed to the increased cognitive load imposed by unfamiliar linguistic structures, which in turn affects task execution speed. Furthermore, physical factors, such as the grip and positioning of the writing tool, also played a role in variations in task performance, demonstrating the importance of considering both cognitive and motor aspects when studying language production.

In conclusion, this research underscores the importance of understanding the neural mechanisms underlying language production, particularly in the context of writing. The study highlights how different brainwave frequencies reflect various cognitive functions, from attention and memory to motor execution, and how these functions interact during complex language tasks.

5. Future Studies

Future studies should explore standardized frameworks for ethical approval in cognitive neuroscience research when working with specialized populations, such as bilinguals, ambidextrous individuals, as the project was first intended; investigating the role of handedness in neural activation by comparing brain activity patterns during linguistic or symbolic tasks among right-handed, left-handed, and ambidextrous individuals which could lead to studies about the neuroplasticity in ambidextrous individuals results in broader or more symmetric channel activation during complex tasks.

Although lateralization was included in the experimental protocol, this study does not provide substantial findings on this aspect as lateralization will be a focus in subsequent phases of a broader research project. Therefore, while the current study does not offer detailed results on this topic, it will be explored in future research endeavors.

Finally, research should investigate how individual variability, including handedness, bilingualism, and cognitive load, affects study outcomes to improve the robustness and applicability of the design.

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Annexes

Annex I: Consent Form



Carta Explicativa

Na primeira tarefa irá visualizar um símbolo cujo terá de recriar com recurso à *smartpen*, no qual é pedido que mantenha a mão com que vai escrever se mantenha o mais estável possível, nas seguintes irá ser-lhe apresentado um vídeo onde será ditada, duas vezes, a palavra que o sujeito terá de escrever, no início tratar-se-ão de pseudopalavras e no final a última tarefa serão palavras correntes comuns.

Irá ser necessário colocar uma touca 10-20 elétrodos de modo a captar os sinais EEG e adicionalmente um EMG durante a realização de toda a prova.

É de realçar que o sujeito poderá abandonar as tarefas a qualquer altura que queira, quer por desconforto e/ou se sinta em alguma situação de stress, no momento o equipamento de teste ser-lhe-á retirado e uma toalha emprestada para que possa lavar o cabelo do gel utilizado no processo dos elétrodos.

Eu, _____, declaro que me voluntario a participar no estudo.

(Assinatura do voluntário)

Data: ___ / _____ de _____

Annex II: Edinburgh Handedness Inventory



Questionário Mão direita ou Mão Esquerda

Nome: _____

É favor indicar com uma (X) a sua preferência em utilizar a mão direita e mão esquerda durante as seguintes tarefas.

Quando a preferência for bastante dominante que faça com que não utilize a sua outra mão, a não ser de maneira forçada, coloque (XX).

Se for indiferente a mão com que realiza a tarefa, coloque uma (X) em ambas as opções.

Algumas atividades requerem a utilização de ambas as mãos. Nesses casos, o objeto cuja mão é requerida encontra-se indicado entre parênteses).

Tarefa / Objeto	Mão esquerda	Mão direita
1. Escrita		
2. Desenhar		
3. Atirar		
4. Tesouras		
5. Escova dentes		
6. Faca (s/ garfo)		
7. Colher		
8. Vassoura (mão acima no cabo)		
9. Acender um fósforo		
10. Abrir uma embalagem		

Annex III: Bilingualism questionnaire



Questionário Bilinguismo

1. Nome Completo: _____
2. Data de Nascimento: ____/____/____
3. Quantas línguas fala fluentemente? _____
4. Quais? _____
5. Desde que idade entrou em contacto com esses idiomas? _____
6. Tem contacto com diferentes idiomas no seu dia a dia? _____
7. Se sim, quais? _____
8. Os seus pais têm alguma outra nacionalidade? _____
9. Se sim, que outras línguas falam fluentemente? _____

Annex IV: Questionnaire



Questionário

10. Nome Completo: _____

11. Data de Nascimento: ____/____/____

12. Qual o seu nível de escolaridade?

- Ensino Básico _____
- Ensino Secundário _____
- Ensino Superior _____
- Analfabeto _____
- Não respondo _____

13. Nas tarefas do dia a dia, qual é a sua mão preferencial?

- Mão Direita _____
- Mão Esquerda _____
- Ambidestro _____
- Não respondo _____

14. Com que línguas entra em contacto no seu dia a dia?

15. Tomou uma refeição antes da realizar o teste? _____

16. Quantas horas costuma dormir por noite, em média?

- Menos de 6 horas _____
- Entre 6 a 8 horas _____
- Mais de 8 horas _____
- Não respondo _____

17. Na noite anterior foi capaz de ter uma boa noite de sono? _____

18. Quantas vezes ingere álcool por dia, em média?

- Menos 2 vezes _____
- Entre 2 a 3 vezes _____
- Mais de 3 vezes _____
- Não respondo _____

19. Ingeriu algum tipo de substância alcoólica antes de realizar o teste? _____

20. Consome algum tipo de substância psicotrópica? _____

21. Toma algum tipo de medicação? _____

22. Utilizará óculos para ler/escrever durante o teste? _____

23. Sofre de algum tipo de patologia diagnosticada?

24. Sofre de epilepsia? _____

25. Possui alguma prótese do membro superior? _____

Annex V: Active channels for the first word of different tasks

First word										
2f_training				2m_training			Portuguese_training			
Writing										
IC	0,5 - 4	4 a 8	8 a 13	0,5 - 4	4 a 8	8 a 13	0,5 - 4	4 a 8	8 a 13	
1										
2			✓			✓			✓	
3										
4						✓				
5						✓				
6										
7			✓			✓			✓	
8			✓						✓	
9			✓	✓		✓	✓	✓	✓	
10			✓							
11						✓			✓	
12								✓		
13			✓			✓			✓	
14			✓			✓			✓	
15			✓							
16	✓		✓	✓		✓	✓		✓	
17			✓			✓			✓	
18			✓			✓			✓	
19			✓			✓			✓	
20			✓		✓	✓			✓	
21									✓	
22						✓			✓	
23	✓		✓	✓		✓	✓		✓	
24			✓		✓	✓			✓	
25			✓		✓	✓		✓	✓	
26		✓				✓			✓	
27			✓			✓		✓	✓	
28										
29			✓		✓	✓			✓	
30			✓			✓			✓	
31			✓			✓		✓		

Annex VI: IC with brain values higher than 95% for the 1st and 3rd word of task 2f_training

2f_training_writing						
Word 1				Word 3		
IC	0,5 - 4	4 a 8	8 a 13	0,5 - 4	4 a 8	8 a 13
1						
2			✓			✓
3						
4						✓
5						
6						✓
7			✓			✓
8			✓			✓
9			✓	✓		✓
10			✓			✓
11						✓
12						
13			✓			✓
14			✓			✓
15			✓			
16	✓		✓	✓		✓
17			✓			✓
18			✓			✓
19			✓			✓
20			✓			✓
21						
22						
23	✓		✓	✓		✓
24			✓			✓
25			✓			✓
26		✓			✓	✓
27			✓			
28					✓	
29			✓			✓
30			✓			✓
31			✓			✓

Annex VII: IC with brain values higher than 95% for the first word of different test tasks

First word									
2f_test				2m_test			portuguese_test		
Writing				Writing			Writing		
IC	0,5 - 4	4 a 8	8 a 13	0,5 - 4	4 a 8	8 a 13	0,5 - 4	4 a 8	8 a 13
1									
2			✓			✓			✓
3						✓			✓
4			✓						✓
5			✓						
6						✓			
7			✓			✓			✓
8			✓			✓			✓
9	✓		✓	✓		✓	✓		✓
10									✓
11			✓			✓		✓	✓
12									
13						✓			✓
14			✓			✓			✓
15			✓			✓		✓	✓
16	✓		✓	✓		✓	✓		
17			✓			✓			✓
18			✓			✓			✓
19		✓	✓		✓	✓		✓	
20			✓			✓		✓	✓
21								✓	✓
22			✓			✓			
23	✓	✓		✓		✓	✓		
24			✓			✓			✓
25						✓			✓
26			✓			✓			✓
27						✓			
28			✓		✓	✓			
29		✓	✓		✓			✓	
30		✓	✓		✓	✓			✓
31						✓			

Annex VIII: Word writing time for Portuguese and English words

Portuguese Words		English Words	
Word	Writing Time (s)	Word	Writing Time (s)
Loja	2	Body	3
Sobrancelhas	5	Chocolate	4
Pão	2	Tomato	3
Cara	2	Banana	4
Harpa	3	Yellow	4
Órgão	2	Happy	5
Carteiro	3	Cinnamon	2
Sardinha	3	Pharmacy	4
Oxigénio	4	Vegetable	4
Higiene	3	Orchestra	4