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Comparative Analysis of neural Activation Patterns during Manual and Digital Writing: An Electroencephalography Study in University Students

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ABSTRACT

The increasing predominance of digital writing in higher education has raised important questions regarding its cognitive and neural implications. This study examines differences in neural activation patterns and neuroeducational markers between manual and digital writing in university students using electroencephalography (EEG) with the Emotiv EPOC+ 14 system. Employing an intrasubject experimental design (n = 10), participants completed equivalent handwritten and typed reflective tasks under controlled conditions. Results revealed that handwriting elicited broader and more bilateral brain activation, associated with greater emotional engagement and sensorimotor integration. In contrast, digital writing showed more focused activation patterns and higher cognitive demand, particularly in working memory-related frequencies. Gender differences were also observed, with males displaying stronger left-hemispheric lateralization and females demonstrating more bilateral activation. These findings provide neurophysiological evidence that writing modality influences cognitive and affective engagement, offering implications for differentiated pedagogical practices in higher education.

Keywords: manual writing; digital writing neural activation; neuroeducation; gender differences

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Introduction

Writing, as a complex cognitive process, has undergone a significant transformation with the introduction of digital technologies in education. The transition from traditional handwriting to digital writing represents not only a change in the medium of expression, but also a potential modification in the underlying neurocognitive processes (James & Engelhardt, 2012; Van der Meer & Van der Weel, 2024).

This transformation raises fundamental questions about how different writing modalities influence cognitive development and neural functioning. These modalities include traditional handwriting with pen and paper, digital handwriting with a stylus on tablets, and keyboard typing on computers or mobile devices. The issue is particularly relevant in higher education contexts, where students engage in advanced tasks such as critical analysis, abstract reasoning, and integrative writing, which place greater demands on executive and language-related neural networks (Longcamp et al., 2005; Van der Weel & Van der Meer, 2023).

This knowledge is crucial to inform educational practices that optimize learning and the development of writing skills in the digital age. Recent neuroimaging research by Van der Weel and Van der Meer (2024) has demonstrated that handwriting generates broader and more elaborate brain connectivity patterns compared to typing, particularly in theta/alpha connectivity coherence patterns between network hubs and nodes in parietal and central brain regions crucial for memory formation and encoding new information. Similarly, studies on the neuroscience of writing modalities indicate that handwriting activates a broader network of brain regions involved in motor, sensory, and cognitive processing, while typing engages fewer neural circuits, resulting in more passive cognitive engagement. These neurological differences have significant implications for academic performance, as handwriting quality shows a direct relationship with academic success in reading and writing (Mueller & Oppenheimer, 2014), and poor handwriting can affect students' ability to organize their ideas, resulting in lower-quality written work. Furthermore, handwriting instruction during university education can improve both writing and reading outcomes (Askvik et al., 2020), making it essential to understand the neural mechanisms underlying different writing modalities in this critical educational context. The unique role of handwriting in developing visual-motor connectivity, as documented by Vinci-Booher et al. (2016, 2021), provides additional evidence for the distinct neural processes involved in manual writing versus typing. This study addresses a significant gap in understanding how these different writing modalities affect neural processing, specifically in university students, where the cognitive demands of education are highest and the implications for learning are most significant (James & Engelhardt, 2012; Van der Meer & Van der Weel, 2017).

In order to address this gap, the study incorporates advanced neuroimaging tools—specifically the Emotiv EPOC+ 14 system and the standardized PRONIN© and SIEN© protocols—which allow for real-time, multidimensional assessment of brain activity and neuroeducational markers in ecologically valid learning conditions. These tools were chosen not only for their validated accuracy in cognitive neuroscience research but also for their ability to provide educationally meaningful interpretations of neural data. Furthermore, the inclusion of gender as a variable is based on robust neuroimaging literature demonstrating sex-based differences in language processing, hemispheric lateralization, and emotional integration during writing tasks (Garn et al., 2009; Shaywitz et al., 1995). By integrating gender analysis into the experimental design, this study aims to uncover potentially divergent neural patterns that may inform more personalized and equitable pedagogical strategies. Thus, the use of these tools and variables strengthens the study's capacity to offer nuanced, evidence-based insights into how writing modalities influence cognition and learning outcomes in diverse student populations.

Review of literature

The present review of literature is organized into five thematic sections. First, it explores the evolution of writing modalities and their impact on cognitive processing. Second, it examines the neural mechanisms activated during handwriting and typing. Third, it considers gender-related differences in neural engagement during writing tasks. Fourth, it presents recent contributions from neuroimaging technologies and educational protocols. Finally, it outlines the theoretical foundations that underpin the current study. Together, these sections provide a comprehensive framework for understanding the neurophysiological dynamics of writing in higher education.

Writing Modalities and Cognitive Processing

Writing modalities and tools have evolved significantly, warranting investigation into their impact on cognitive development and neural processing, particularly in higher education contexts.

Previous studies on the differences between manual and digital writing, such as those by Longcamp et al. (2005), Mueller and Oppenheimer (2014) have mainly focused on behavioral and academic performance aspects. These studies have examined differences in letter recognition, spelling accuracy, memory recall, and note-taking efficiency between handwriting and typing modalities. However, there is a significant gap in understanding the neurophysiological mechanisms underlying both writing modalities, especially in the university context (Van der Meer & Van der Weel, 2023). This gap is particularly significant because digital writing devices have become ubiquitous in higher education classrooms worldwide, substantially reducing the use of longhand writing despite limited understanding of its cognitive implications (Pérez Alonso, 2015). University students face unique cognitive demands that make this research especially relevant: they must engage in complex analytical thinking, synthesize information from multiple sources, produce sophisticated written arguments, and transfer knowledge across domains. Recent neuroimaging research with university students has revealed that the brain's connectivity patterns differ significantly between handwriting and typing, with implications for learning and memory formation that are crucial at this educational level (Vinci-Booher et al., 2021). Understanding these neurological differences can provide insights into optimal learning strategies for higher education, where cognitive demands require deeper processing and engagement with complex material (Marano et al., 2025).

Neural Mechanisms in Handwriting and Typing

Research in cognitive neuroscience has shown that handwriting involves specific neural networks that integrate motor, visual, and cognitive functions (James & Engelhardt, 2012). These neural processes are fundamental to the development of literacy skills and learning in general. On the other hand, digital writing, which has gained prevalence in the current educational context, involves different patterns of motor and cognitive activation. These studies, likewise, have revealed that handwriting activates specific neural networks that uniquely integrate motor, somatosensory, and visual areas. This multimodal activation has been associated with improvements in working memory, conceptual understanding, and long-term retention (James & Engelhardt, 2012). Mueller and Oppenheimer (2014) demonstrated that students who take notes by hand tend to engage in deeper cognitive processing, including summarization, paraphrasing, and conceptual integration, rather than simply transcribing content verbatim. This deeper processing is associated with improved long-term retention and understanding of complex material. In contrast, digital writing—particularly typing—offers certain pragmatic advantages such as faster transcription speed, the ability to easily reorganize content, and the use of digital tools (e.g., cut, copy, paste, and formatting features). These features can enhance efficiency and facilitate the production of longer, more structured texts, although they may also lead to more superficial processing if not accompanied by active engagement strategies (Bui et al., 2013; Morehead et al., 2019).

Gender Differences in Neural Activation

Gender differences in cognitive and linguistic processing have been extensively documented in neuroscientific literature. For example, neuroimaging studies have shown that males tend to exhibit greater left-hemisphere lateralization during language tasks, while females often display more bilateral activation across both hemispheres (Garn et al., 2009; Shaywitz et al., 1995). These activation patterns suggest that males may rely more heavily on localized and task-specific processing, particularly in regions associated with phonological and syntactic operations, whereas females tend to engage broader and more integrated neural networks that involve emotional, cognitive, and visual-motor areas. Such differences in neural architecture may influence how each gender engages with writing tasks, both in terms of processing strategies and emotional involvement.

Neuroimaging Tools and Educational Protocols

Moreover, studies by Hernandez and De Barros (2022) at the University of Jaén, with university students, showed that neuroimaging provides a valuable tool to examine these neural processes in real time. The use of the Emotiv EPOC+ 14 system, together with the standardized protocols PRONIN© and SIEN©, allows a detailed analysis of brain activation patterns, waves, and neuroeducational markers associated with different writing modalities. The integration of advanced neuroimaging technologies with standardized protocols represents a significant advance in the understanding of cognitive processes during writing. The Emotiv EPOC+ 14 system, widely validated in cognitive neuroscience research (Badcock et al., 2013; Duvinage et al., 2013), enables accurate and noninvasive measurement of brain activity in real time. This device has proven to be effective in recording electroencephalographic signals in both experimental and educational applications, standing out for its high temporal resolution and ease of use in non-clinical settings (Debener et al., 2012; De Vos et al., 2014). The PRONIN© and SIEN© protocols have been developed specifically for the educational context, providing a robust methodological framework for the interpretation of neurophysiological data in learning environments.

Theoretical Frameworks Underpinning the Study

These protocols are particularly valuable for this study because recent advances in network science offer unique tools for understanding learning supported by distributed neural circuits, providing insights into adaptive neural processes, knowledge attainment, and skill acquisition (Bassett et al., 2017). Understanding the neurophysiological mechanisms underlying different learning modalities is essential as they connect changes in neurophysiology directly to changes in behavior, offering quantitative theories that can better inform educational practice (Bassett & Mattar, 2017).

Furthermore, recent advancements in neuroimaging technologies have significantly contributed to our understanding of how the brain processes information during learning, revealing the intricate workings of memory, attention, and cognitive functions crucial for education. Functional neuroimaging captures the brain's neurophysiological properties, which are particularly relevant for understanding the multivariate nature of the brain and how it processes writing through different modalities.

Given these advances, the present research aims to fill a critical gap by studying the specific neural activation patterns associated with different writing modalities in university students, where the cognitive demands require more complex processing and integration across brain regions. This knowledge will provide evidence-based insights for optimizing learning strategies in higher education settings where writing remains a fundamental tool for academic success.

With all of the above, the present research seeks to deepen the understanding of how different writing modalities affect neural activation patterns and cognitive processes in college students. This knowledge is crucial to inform educational practices that optimize learning and the development of writing skills in the digital age.

This study is grounded in three main theoretical pillars that provide a comprehensive framework for understanding the neurophysiological mechanisms underlying different writing modalities:

1. The theory of hemispheric specialization in language processing posits that the left hemisphere is typically dominant for language in right-handed individuals, particularly involving Broca's area (speech production) and Wernicke's area (language comprehension) (Broca, 1865; Geschwind, 1970; Wernicke, 1874). This framework is essential for interpreting differences in hemispheric activation observed during handwriting and typing tasks.

2. The sensorimotor integration model of learning emphasizes that learning processes are enhanced when motor and sensory systems are jointly activated. Writing by hand involves fine motor control, tactile feedback, and visual monitoring, engaging distributed neural networks that support memory encoding and cognitive elaboration (James & Engelhardt, 2012). This model helps explain why handwriting may induce broader and more integrated neural activation.

3. The theory of gender differences in cognitive processing is supported by neuroimaging evidence showing that males tend to process language more laterally in the left hemisphere, while females display more bilateral activation patterns, potentially reflecting greater interhemispheric integration (Garn et al., 2009; Shaywitz et al., 1995). This theory informs the gender-based analysis in our study, helping interpret divergent patterns in neural activation and neuroeducational markers between male and female participants.

Together, these theoretical models support the design, interpretation, and relevance of our findings, providing a multidimensional lens for analyzing the neural dynamics of writing across modalities and genders.

Research Questions and Educational Relevance

The convergence of these theoretical perspectives offers a solid foundation for analyzing the neural mechanisms involved in different writing modalities, capturing both their cognitive structure and their educational relevance. Grounded in this framework, the present study seeks to respond to the following research questions:

What distinct patterns of hemispheric, lobar, and brainwave activation emerge when university students engage in manual writing as opposed to digital writing?

In what ways do neuroeducational markers—such as attention, engagement, emotional response, interest, relaxation, and stress—vary between the two modalities?

How does gender modulate the relationship between writing modality and hemispheric lateralization in neural activity?

These questions aim to unravel the neurophysiological underpinnings of writing, particularly in higher education contexts where academic tasks demand elevated levels of abstraction, integration, and cognitive flexibility. Understanding these neural dynamics can contribute to designing more effective and inclusive pedagogical practices adapted to students' cognitive profiles.

Method

The present study implements an intrasubject experimental design with repeated measures, where each participant performs two writing tasks (manual and digital) under controlled conditions. This methodological approach allows for direct comparison of neural activity patterns within the same individual across different writing modalities, effectively controlling for individual differences in brain structure and function.

In this design, all participants experience both experimental conditions—handwriting and digital writing—which increases statistical power while requiring fewer participants than between-subjects designs. This approach is particularly valuable for neurophysiological research, as it enables the detection of subtle differences in brain activation that might otherwise be masked by inter-individual variability.

To mitigate potential order effects, where performance in one condition might influence the subsequent condition, counterbalancing techniques are employed by systematically varying the sequence of writing tasks across participants. This ensures that any practice or fatigue effects are distributed equally across conditions, preserving the internal validity of the study (McLeod, 2023).

This within-subjects design is particularly valuable for neurophysiological research, as it enhances statistical power while minimizing the influence of inter-individual variability and other confounding factors. It also allows for the detection of subtle differences in brain activation patterns across writing modalities (Charness et al., 2012). By having each participant serve as their own control, the design effectively isolates the effects of writing modality from other potential sources of neurophysiological variation, such as individual differences in baseline brain activity, age-related neural changes, or varying levels of expertise with writing modalities.

The intrasubject design also provides practical advantages for neuroimaging research, as it maximizes the information obtained from each participant while requiring fewer overall subjects, an important consideration given the resource-intensive nature of EEG studies (Little et al., 2020).

The primary aim of this study was to examine differences in neural activation patterns and neuroeducational markers during manual pen writing and digital computer writing in university students using electroencephalography. More specifically, the research sought to identify modality-specific hemispheric, lobar, and brainwave activation patterns while considering potential gender differences. In addition, the study compared neuroeducational markers, including attention, engagement, emotional response, interest, relaxation, and stress, across writing modalities and genders. It also explored the relationship between writing modality and hemispheric lateralization, focusing on the activation of specific cortical regions.

Based on previous literature on sensorimotor integration, hemispheric specialization, and gender-related differences in language processing, three hypotheses were formulated. First, it was expected that handwriting would generate broader and more bilateral neural activation patterns than digital writing. Second, manual writing was hypothesized to be associated with higher levels of emotional engagement compared to digital writing. Third, significant gender differences in neural activation patterns were anticipated across both writing modalities.

The hypotheses are based on previous studies on hemispheric lateralization and gender differences in language processing. H1 is based on literature suggesting greater sensorimotor integration during handwriting.

H2 is grounded in prior research highlighting the affective dimension of handwriting. For example, Pennebaker and Chung (2011) demonstrated that expressive writing tasks involving manual inscription are associated with stronger emotional processing and autobiographical integration, suggesting that the physical act of writing may enhance affective engagement. Similarly, Smorti and Fioretti (2016) reported that writing about emotional experiences by hand can intensify emotional elaboration and self-reflective processing. These findings support the expectation that manual writing may generate higher levels of emotional engagement than digital writing. H3 is supported by neuroimaging studies documenting sex-related differences in language processing and hemispheric lateralization. Shaywitz et al. (1995), using functional neuroimaging, reported greater bilateral activation in females during language tasks, whereas males exhibited more left-hemispheric lateralization. Likewise, Garn et al. (2009) identified sex differences in cortical activation patterns during lexical processing tasks. These findings provide a theoretical basis for anticipating gender-based differences in neural activation patterns across writing modalities.

Variables

Independent variables: writing modality (manual vs. digital); gender (male vs. female).

Dependent variables: neural activation patterns [hemispheric activation (left/right), lobar activation (frontal, temporal, parietal, occipital) and brain wave types (theta, alpha, beta, gamma)], neuroeducational markers [level of attention, level of task engagement, level of emotions, level of interest, level of relaxation, level of stress].

Participants

The sample, by convenience, consisted of 10 university students (5 men and 5 women) in the last year of the Degree in Primary Education at the University of Jaén. The age of the participants ranged from 21 to 23 years (M = 21.8, SD = 0.63). Inclusion criteria were: right manual dominance, normal or corrected vision, no history of neurological or psychiatric disorders, and Spanish as mother tongue.

The selection of the sample size was based on previous neuroimaging studies on handwriting processing (Dehaene et al., 2015) that show that a sample of 10 participants allows detecting significant effects in neural activation paradigms. Controlling for right manual dominance is crucial according to Geschwind and Galaburda (1985) findings on language lateralization, which established that 95% of right-handers exhibit left hemisphere dominance for language. The equal inclusion by gender responds to the neurobiological differences in language processing documented by Shaywitz et al. (1995).

All ethical procedures for this study were carried out in accordance with international research standards and approved by the institutional ethics committee of the University of Jaén. Prior to participation, all individuals received detailed information about the study and signed informed consent forms. Personal data were anonymized and processed in compliance with the General Data Protection Regulation (GDPR). To ensure data validity and participant safety, strict exclusion criteria were applied: history of cranioencephalic trauma, use of psychoactive medication, diagnosis of learning disorders, or prior experience in EEG-based research. These measures aimed to reduce potential confounding variables and ensure a homogenous and neurologically healthy sample.

Instruments

The Emotiv EPOC+14 system, a non-invasive electroencephalography device with 14 recording channels (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4) and two references in the mastoid (CMS/DRL), was used to record brain activity. The device operates at a sampling rate of 128 Hz, providing high temporal resolution data on brain activity. The selection of this system is based on its validation for research in cognitive neuroscience, specifically in the study of writing and language processes (Badcock et al., 2013). The 14 channels allow recording activity in areas critical for linguistic and motor processing, including the fronto-temporal networks involved in written production.

Writing Assignments

To compare neural activation between writing modalities, two equivalent writing tasks were developed—one manual and one digital—based on a reflective composition. In the manual writing condition, participants were instructed to write a reflective text using a standard blue ballpoint pen on lined A4 paper, while seated in an ergonomically adjusted chair and desk. In the digital writing condition, participants typed the same type of reflective composition on a 15-inch laptop with a standard QWERTY keyboard, using a basic word processor (no autocorrect or grammar aids activated). Reflective writing was selected as the task type because it activates a broad range of cognitive and emotional processes, including autobiographical memory, language generation, and affective engagement, making it especially suitable for detecting modality-specific differences in neural activation (Pennebaker & Chung, 2011; Smorti & Fioretti, 2016).

For both conditions, participants received standardized instructions, delivered verbally by the researcher:

"You will have 15 minutes to write a reflective text on the topic provided. Try to express your thoughts clearly and continuously, as if you were writing for a university assignment. Avoid long pauses or editing; the goal is to maintain a steady writing flow for the full duration."

The topic remained identical in both modalities to ensure content equivalence. Additionally, environmental variables—such as lighting (500–750 lux), temperature (20–22°C), background noise (≤35 dB), and posture—were carefully controlled and maintained constant across all sessions. These measures were implemented to reduce potential confounding variables and ensure valid comparison of neural responses across writing formats.

Operational Neuroimaging Protocol (PRONIN©)

Electroencephalographic recordings were conducted following the PRONIN© (Protocol for Neuroimaging in Neuropedagogical Research), which is organized into three sequential phases. The pre-registration phase (15 minutes) included the verification of signed informed consent, standardization of environmental conditions (illumination: 500–750 lux; temperature: 20–22°C), assessment of participant readiness (alertness, comfort, and baseline state), and elimination of electromagnetic interference from the recording space.

Specifically, this study followed strict ethical and control procedures to ensure data integrity and participant safety. Informed consent was obtained from all participants, and data protection complied with GDPR regulations through anonymization and restricted access. Exclusion criteria—such as history of cranioencephalic trauma, use of psychoactive medication, diagnosed learning disorders, or prior EEG experience—were applied to reduce variability. Environmental conditions were standardized (lighting, temperature, electromagnetic control) according to the

PRONIN© protocol, ensuring consistent recording conditions. These procedures were approved by the institutional ethics committee and aligned with international research standards.

The second phase, which involved device preparation and baseline recording, lasted approximately 15 minutes, involved calibration of the Emotiv EPOC+ device (10 minutes), placement of electrodes following the International 10–20 System, and baseline EEG recording with eyes open (3 minutes) and closed (3 minutes).

The final experimental phase (45 minutes) consisted of two writing tasks (manual and digital), each lasting 15 minutes, separated by a 15-minute rest period to prevent cognitive fatigue and order effects, as recommended in cognitive neuroscience protocols involving sustained attention tasks (Luck, 2014; Wascher et al., 2014). The order of tasks was counterbalanced across participants to control for order effects and mitigate sequence-related biases, as recommended in EEG experimental design to ensure internal validity (Luck, 2014).

Neuroimaging Analysis Protocol (SIEN©)

Electroencephalographic data were analyzed using the SIEN© (Standardized Interpretation System for Neuroimaging), which incorporates three complementary analytical dimensions. The structural dimension focuses on the analysis of hemispheric lateralization, the regional characterization of activation by cerebral lobes (frontal, parietal, temporal, occipital), and the evaluation of inter- and intra-hemispheric connectivity patterns.

The functional dimension involves spectral analysis of the main EEG frequency bands—theta, alpha, beta, and gamma—as well as the temporal sequencing of neural activation and the quantification of neuroeducational markers, including attention, engagement, and stress.

Finally, the contextual dimension integrates procedural and environmental variables recorded during the experiment and includes documentation of the participant's condition during the data acquisition process. This multimodal approach allows for a comprehensive interpretation of brain activity in natural learning contexts.

Data analysis

The data analysis implemented in this study was structured in three fundamental phases to examine the patterns of neural activation during the different writing modalities.

In the initial phase, the electroencephalographic signals obtained with the Emotiv EPOC+ 14 were preprocessed by applying digital filtering techniques (0.5-45 Hz) and baseline correction, ensuring a minimum quality threshold of 95% according to the PRONIN© protocol.

The second phase consisted of spectral analysis of the EEG signals using fast Fourier transform (FFT), identifying four primary frequency bands: theta (4–8 Hz), associated with working memory; alpha (8–13 Hz), linked to attentional control; beta (13–30 Hz), related to concentration; and gamma (30–100 Hz), reflecting high-level cognitive integration. Measures of signal power and inter-electrode coherence were computed to evaluate functional brain connectivity.

The final phase incorporated the analysis of the neuroeducational markers of the SIEN© system (attention, engagement, emotions, interest, relaxation, and stress).

Results

Analysis of electroencephalographic recordings during manual and digital writing tasks revealed distinctive patterns of neural activation that vary by both writing modality and gender. The results are structured according to three key moments in the writing process, represented in the images shown below.

Detailed results of the neural activation patterns for each participant and writing modality are presented below, organized in figures (1,2,3,4) showing the different experimental conditions.

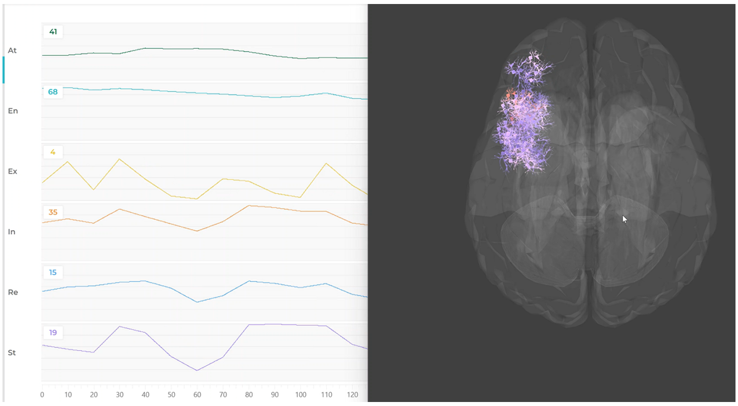

Figure 1. Male. Writing with a ballpoint pen

In terms of brain activation, neuroimaging shows a predominantly lateralized pattern in the left hemisphere, which is consistent with language processing and fine motor functions associated with writing. Specifically, we observed:

In the left frontal lobe, the participant exhibited relatively reduced neural activation, which may suggest a more automated motor processing pattern during the handwriting task. Despite this reduced activity, the presence of beta waves was notable, indicating a state of active concentration and conscious cognitive processing. In contrast, the left temporal lobe showed more extensive activation than the frontal region, with a predominance of beta waves, reflecting active linguistic processing. Additionally, gamma activity—particularly in the form of gamma dots—was observed, suggesting high-level cognitive integration and complex information processing. The analysis of neuroeducational markers revealed a moderate level of attention (41%), consistent with sustained but not intensive concentration, and a relatively high degree of task engagement (68%), indicating solid involvement in the activity. Emotional involvement was notably low (4%), which may reflect a more mechanical or automatic execution of the task. Similarly, interest was moderate to low (35%), potentially related to task familiarity, while relaxation levels were also low (15%), suggesting some tension during the task. However, the stress level remained relatively low (19%), indicating that the activity did not produce significant psychological pressure.

This pattern of activation suggests that handwriting in this male participant is characterized by predominantly analytical and linguistic processing in the left hemisphere. The execution appears relatively automated, accompanied by a moderate level of conscious attention. Despite this automation, the participant demonstrated significant commitment to the task, although with minimal emotional involvement. Overall, the neurophysiological and neuroeducational data indicate a state of active alertness, yet without notable levels of stress.

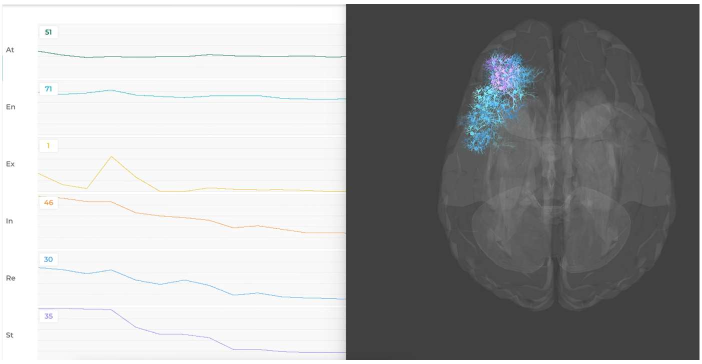

Figure 2. Male. Writing on a computer

In terms of brain activation, neuroimaging maintains lateralization in the left hemisphere, but with different activation patterns than those observed in handwriting. Specifically:

In the left frontal lobe, a significant shift was observed in the type of brain waves during the digital writing condition. Specifically, theta waves (4–8 Hz) emerged alongside beta waves, indicating that the participant was engaging in working memory processes and encoding new information. This shift suggests a transition toward more conscious and deliberate cognitive processing compared to the manual writing condition. The persistence of beta waves confirms the maintenance of active attention throughout the task. Neural activation in the temporal lobe remained present but showed a different pattern than during handwriting, potentially reflecting an adaptation of linguistic processing to the digital modality. Neuroeducational markers also displayed notable changes: attention increased markedly from 41% to 51%, implying heightened cognitive focus during digital writing. Task engagement rose slightly (from 68% to 71%), indicating consistent involvement. In contrast, emotional activation decreased from 4% to 1%, pointing to a more mechanical and less affective interaction with the task. Interestingly, interest levels rose from 35% to 46%, possibly due to the novelty or increased cognitive challenge of digital input.

Relaxation also doubled (from 15% to 30%), which may reflect greater familiarity or ease with digital tools. However, stress levels increased sharply from 19% to 35%, suggesting that the cognitive demands of digital writing may provoke a more complex neurophysiological response. Although the same topic was used in both tasks, and the order of tasks was counterbalanced across participants to control for topic familiarity and learning effects, the combination of increased attention and stress may also reflect the specific motor-cognitive demands of typing. All participants were experienced in digital writing due to their academic background, which reduces the likelihood that differences were driven by disparities in typing competence. Altogether, these findings in the male participant indicate a clear shift from more automated processing in handwriting to more effortful and cognitively engaged processing in digital writing. Although left hemispheric lateralization was maintained, the distribution of activation suggests a change in processing strategies between modalities, highlighting the differential cognitive and emotional demands posed by each.

Hemispheric Activation Patterns:

In both writing modalities, a clear lateralization in the left hemisphere is maintained, which is consistent with language processing and motor functions. However, the distribution of activation within this hemisphere shows significant differences according to the writing modality.

Lobular activation patterns revealed clear distinctions between the two writing modalities. During manual writing (Figure 1), neural activity was more concentrated, with reduced activation in the frontal lobe and greater engagement in the temporal region, suggesting a more localized and possibly automatized cognitive process. In contrast, digital writing (Figure 2) showed a more balanced distribution of activation across both frontal and temporal lobes, indicative of more integrated and distributed processing. The analysis of brainwave patterns further underscored these differences. In the manual writing condition, beta waves predominated in both lobes, with some gamma activity observed in the temporal lobe, reflecting a more automated and efficient mode of processing. Conversely, digital writing was characterized by the emergence of theta waves alongside beta waves in the frontal region, pointing to a shift toward more conscious processing and increased use of working memory. Neuroeducational markers showed significant changes across conditions. Attention levels increased from 41% in manual writing to 51% in digital writing, suggesting a higher requirement for cognitive focus in the latter. Task engagement remained high in both conditions, rising slightly from 68% to 71%. Emotional engagement, however, declined from 4% to just 1% in the digital modality, indicating a more mechanical approach. Interest rose substantially (from 35% to 46%), possibly due to the more challenging or novel nature of digital input. Relaxation levels doubled (from 15% to 30%), pointing to greater physical comfort, yet this was accompanied by a substantial increase in stress (from 19% to 35%), which may reflect the cognitive demands of multitasking during typing. These findings suggest that digital writing involves more deliberate and focused cognitive effort, increased attentional load, and a paradoxical coexistence of physical ease and mental strain.

Consequently, handwriting and digital writing may serve distinct pedagogical functions: the former fostering emotional engagement and fluency, and the latter enhancing attentional control and processing precision. While these differences are consistent with prior neuroeducational findings, we acknowledge that the repetition of the same writing topic across both conditions may have contributed in part to the observed cognitive and emotional patterns. However, the counterbalanced design and the open-ended, reflective nature of the task aimed to minimize the influence of task repetition.

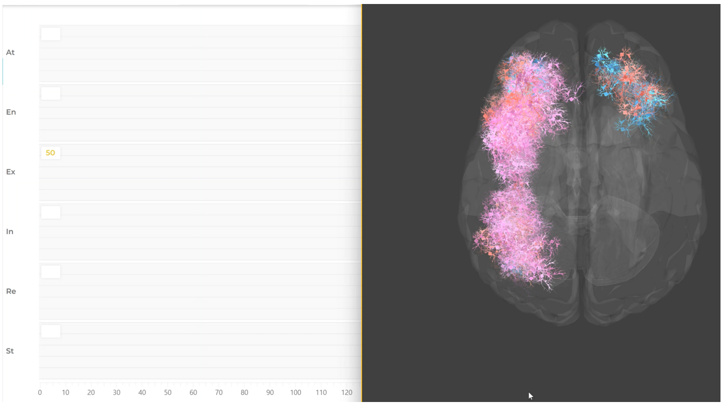

Figure 3. Female. Writing with a ballpoint pen

In contrast to the predominantly lateralized activation observed in the male participant, the neuroimaging of the female participant shows significant bilateral activation, involving both cerebral hemispheres. This more distributed activation pattern suggests a more integrated processing during handwriting.

In the left hemisphere, we observed extensive activation spanning multiple regions:

The frontal and temporal lobes show a rich combination of neural activity:

- Theta waves in the frontal area, indicating active working memory and planning processes.

-Gamma waves overlapped in these regions, suggesting high-level cognitive processing and information integration.

- The presence of alpha waves in other areas indicates an active but controlled processing state.

The parietal and occipital lobes also show significant activation:

- The presence of alpha waves in these regions suggests active visual-spatial processing.

- This later activation could be related to the visual-motor integration necessary for handwriting.

In the right hemisphere, activation is concentrated in:

- Frontal lobe, with a combination of theta and gamma waves, suggesting creative processes and emotional integration.

- The upper part of the temporal lobe, showing a similar pattern of waves.

A particularly interesting finding is the neuroeducational marker of emotions, which reaches 50%. This high level of emotional activation contrasts sharply with that observed in the male participant (4%) and suggests a greater affective involvement in the handwriting task.

This brain activation configuration suggests that the female participant is employing:

1. More holistic processing that integrates cognitive, emotional, and motor functions.

2. Increased involvement of areas related to creativity and emotional processing.

3. A writing strategy that involves both mechanical and expressive aspects.

4. A more integrated approach combining analytical and global processing

The presence of gamma waves in multiple regions, together with bilateral activation, suggests a more complex and multifaceted processing of the writing task. This pattern could indicate a greater integration between the mechanical aspects of writing and higher-order cognitive processes. The high level of emotional arousal may be related to a greater personal connection to the handwriting task, suggesting that this modality may be particularly beneficial for tasks that require personal expression or creativity.

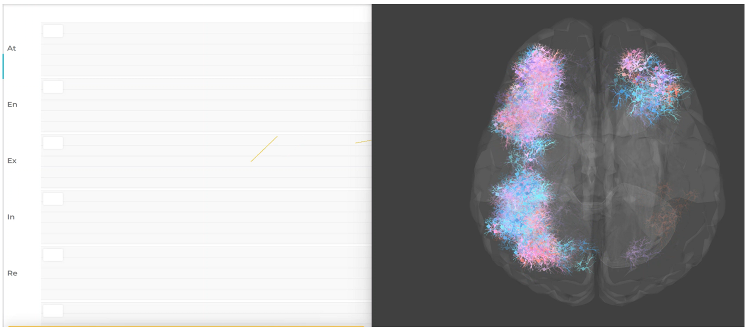

Figure 4. Female. Writing with a computer

As observed in the handwriting condition, bilateral activation was also maintained during digital writing, although with distinct patterns that suggest different underlying processing mechanisms. Let us look in detail at the activation by hemispheres:

In the left hemisphere, we observed a complex pattern of neural activation, particularly in the frontal and temporal lobes. These regions showed a combination of theta and alpha wave activity. Theta waves suggest the engagement of active working memory and planning processes, while the predominance of alpha waves indicates a state of controlled, and possibly more automated, cognitive processing.

The parietal lobe shows theta waves, which could be related to the sensorimotor integration required for digital writing.

The occipital lobe shows activation with gamma waves, suggesting intensive visual processing, possibly related to the need to monitor the screen during typing.

In the right hemisphere, neural activation was primarily concentrated in the frontal and superior temporal lobes. Within these regions, alpha wave activity was evident, particularly in the temporal area and parts of the frontal lobe, suggesting a state of calm, focused attention. Additionally, theta waves emerged in specific areas, indicative of ongoing working memory processes. Notably, gamma activity—reflected in the presence of gamma "dots" in the temporal lobe—suggested high-level cognitive integration and semantic processing.

A particularly interesting aspect is the absence of specific neuroeducational markers, which contrasts markedly with the high emotional activation (50%) observed during manual writing.

This absence could suggest a more mechanical and less emotionally involved processing during digital writing. Notably, in this case, the participant completed the handwriting task first, followed by the digital writing task. The reduction in emotional engagement may therefore reflect not only differences in writing modality but also the possible influence of task repetition or diminished novelty in the second condition.

A comparison with the handwriting condition (Figure 3) reveals notable differences in the participant's neural activation patterns. Although both modalities maintain bilateral activation, digital writing exhibits a more specific and localized distribution of brain activity. This shift is accompanied by a change in the predominant brainwave types, with a greater presence of alpha waves, which may reflect more automated yet controlled cognitive processing. Moreover, gamma activity in the occipital lobe suggests increased demands on visual processing, likely due to the need for continuous screen monitoring during typing. Notably, the absence of neuroeducational markers in this condition may indicate a transformation in the nature of task engagement, moving from a more emotionally involved state during handwriting to a more cognitively focused and analytical one in digital writing.

Taken together, this activation pattern during digital writing suggests that the participant adopts a more structured and emotionally detached processing style, marked by enhanced visual-motor coordination and a heightened level of cognitive control. The mental state appears to be more task-oriented and efficiency-driven, in contrast to the expressive and affectively rich engagement observed in handwriting. These modality-dependent differences in neural dynamics underscore the distinct ways in which manual and digital writing influence not only cognitive operations but also emotional and expressive dimensions of written language production.

Comparison of Figures 3 and 4:

Hemispheric Activation Patterns:

Bilateral activation is maintained in both writing modalities, suggesting an integrated processing characteristic of the female brain. However, the nature of this bilateral activation shows significant differences between the two writing modalities. During handwriting (Figure 3), we observed a more extensive and distributed activation spanning multiple brain areas in both hemispheres. This activation includes frontal, temporal, parietal, and occipital lobes, suggesting a more holistic and integrated processing. In contrast, during digital writing (Figure 4), although bilaterality is maintained, activation appears more focused and specific in certain regions, particularly in the frontal and temporal lobes.

Brainwave Distribution:

During handwriting, the participant exhibited a rich and diverse combination of brainwave activity. Theta and gamma waves were observed in the frontal lobe, indicating an active integration of working memory with high-level cognitive processes. Alpha waves appeared across several brain regions, suggesting a state of sustained but regulated cognitive engagement. Notably, the consistent presence of gamma waves pointed to complex and multifaceted processing, likely associated with semantic elaboration, creativity, and emotional integration. In contrast, the digital writing condition showed a markedly different brainwave profile. Alpha and theta waves predominated in the frontal and temporal lobes, reflecting a more focused but controlled form of cognitive engagement. Additionally, gamma waves emerged specifically in the occipital lobe, a pattern that may be attributed to the increased visual monitoring required when typing on a screen. Overall, the distribution of brainwaves during digital writing appeared more structured and less variable, indicating a shift toward a more uniform and perhaps efficiency-driven processing style.

Emotional and Cognitive Aspects:

The most notable difference is found in the neuroeducational markers:

- Handwriting shows a significantly high emotional score (50%), suggesting a strong emotional connection to the task.

- Digital handwriting does not show specific neuroeducational markers, which could indicate more mechanical and less emotional processing

This difference in emotional arousal suggests that handwriting may be more linked to processes of self-expression and creativity, whereas digital writing may favor more systematic and task-oriented processing.

Male-female comparison:

Fundamental Differences in Processing:

During handwriting, we found a first fundamental difference in brain lateralization. The male participant shows a marked lateralization in the left hemisphere, with activation concentrated mainly in the frontal and temporal lobes. In contrast, the female participant exhibits significant bilateral activation, involving multiple brain regions in both hemispheres. This difference suggests that females tend to employ more integrated and holistic processing during handwriting. In digital writing, although both genders show adaptations in their activation patterns, they maintain distinct characteristics. The male participant continues with lateralized processing but with a redistribution of resources, while the female participant maintains bilaterality although with more focused patterns than in handwriting.

Brainwave Patterns:

In the male case, we observed an interesting transition between writing modalities. During manual writing, beta waves predominate with some gamma dots, suggesting more automated processing. When switching to digital writing, theta waves appear along with beta, indicating more conscious processing and greater use of working memory. The female participant shows a greater variety of brain waves in both modalities. During manual writing, she presents a rich combination of theta, gamma and alpha waves distributed in different brain regions. In digital writing, while maintaining this variety, there is a shift towards a predominance of alpha and theta waves, with gamma waves specifically in the visual area.

Neuroeducational markers

The differences in neuroeducational markers are particularly revealing:

Male Participant:

- Manual Writing: attention (41%), engagement (68%), emotions (4%), interest (35%), relaxation (15%), stress (19%)

- Digital Writing: attention (51%), engagement (71%), emotions (1%), interest (46%), relaxation (30%), stress (35%)

Female Participant:

- Manual Writing: highlights a high emotional level (50%)

- Digital Writing: absence of specific neuroeducational markers.

This comparison reveals that the male participant shows quantifiable changes in the markers between modalities, while the female participant shows a marked qualitative difference, especially in the emotional component.

Discussion

This study provides compelling evidence for distinct neurophysiological patterns between manual and digital writing modalities, as well as notable gender differences in neural processing during writing tasks. The term "compelling" is supported by consistent patterns observed in EEG activation across participants, including modality-specific changes in brainwave frequencies (e.g., beta and gamma during handwriting vs. theta and alpha during digital writing) and hemispheric lateralization differences by gender. These findings align with and expand upon prior research by Van der Meer and Van der Weel (2024), who demonstrated broader cortical connectivity during handwriting, and Garn et al. (2009), who documented sex differences in neural activation during language tasks.

However, this study adds further depth by integrating neuroeducational markers—such as attention, emotional engagement, interest, relaxation, and stress—measured in real time through electroencephalography and interpreted via standardized protocols specifically designed for educational settings. The PRONIN© protocol structures the neuroimaging procedure through three defined phases (preparation, baseline recording, and task execution), ensuring environmental consistency and participant readiness. The SIEN© system, in turn, enables a multidimensional analysis of EEG data by combining structural brain activation (e.g., hemispheric and lobar), functional dynamics (e.g., frequency band patterns), and contextual factors (e.g., participant emotional state and environmental conditions). Unlike previous research that often isolates EEG measures from educational constructs, these protocols were specifically developed to bridge neuroscience and pedagogy. As such, they offer a more ecologically valid and pedagogically meaningful interpretation of neural activity during complex cognitive tasks like writing. Beyond the neurophysiological differences observed across writing modalities, the pedagogical dimension of instructional decision-making becomes central. Recent research published in the *Iranian Journal of Language Teaching Research* has emphasized the role of teacher self-efficacy and instructional design in shaping learner engagement in complex language tasks (Karimi, Marashi, & Mall-Amiri, 2025). In this regard, understanding how handwriting and digital writing differentially activate cognitive and emotional processes may support more informed pedagogical choices, particularly in higher education contexts where advanced writing demands interact with instructional strategies and learner self-regulation.

While some studies have highlighted general cognitive differences between writing modalities (e.g., James & Engelhardt, 2012; Mueller & Oppenheimer, 2014), this research uniquely contributes by offering fine-grained neurophysiological data that capture moment-to-moment cognitive and emotional engagement, particularly in university students. Therefore, the study extends existing literature by combining neuroimaging, gender analysis, and educational variables in a single experimental framework.

The observation of broader bilateral activation during handwriting, particularly in female participants, aligns with previous findings by James and Engelhardt (2012), who demonstrated that handwriting activates a complex network of sensorimotor and cognitive regions, including frontal, parietal, and temporal areas. This multisensory engagement supports deeper semantic encoding and cognitive integration. Furthermore, Mueller and Oppenheimer (2014) showed that handwriting fosters superior content retention and conceptual processing compared to typing, likely due to this richer neural involvement. Our study not only confirms these neural patterns but adds a critical gender-based perspective by showing that female participants exhibited consistently more bilateral activation than males in both writing modalities, with particularly strong engagement during handwriting. This bilateral pattern may reflect enhanced interhemispheric communication, possibly linked to sex-based neuroanatomical differences such as a larger corpus callosum or increased gray matter symmetry, as suggested by Shaywitz et al. (1995) and Garn et al. (2009). Such interhemispheric integration could enable females to simultaneously process emotional, linguistic, and visual-motor aspects of handwriting, leading to more expressive and cognitively enriched written output. In contrast, the more lateralized activation observed in male participants may indicate a task-specific reliance on left-hemispheric networks for linguistic and motor control, with reduced emotional or integrative processing.

The marked differences in emotional engagement between writing modalities represent a particularly noteworthy finding. The significantly higher emotional markers during handwriting (50% in female participants versus 4% in male participants) suggest that the sensorimotor experience of manual writing may facilitate stronger emotional connections to the content. This finding extends beyond previous research that has primarily focused on cognitive and academic outcomes, such as note-taking efficiency, memory retention, and conceptual understanding (e.g., Mueller & Oppenheimer, 2014; Longcamp et al., 2005; Van der Meer & Van der Weel, 2024). Our results suggest that handwriting not only activates more diverse cortical regions but also enhances emotional resonance with the written content, particularly in female participants. This emotional encoding may contribute to higher levels of motivation, personal expression, and memory consolidation, supporting the idea that writing modality influences both cognitive and affective aspects of learning. Therefore, our study adds an important layer to the existing literature by demonstrating that writing is not only a cognitive act but also an emotionally embodied process, especially when mediated through manual modalities.

Digital writing's association with more focused activation patterns and increased stress levels, particularly in male participants (35% versus 19% in manual writing), suggests a different type of cognitive engagement. The appearance of theta waves during digital writing, especially in frontal regions, reflects heightened demands on working memory, likely due to the dual requirement of managing typing mechanics while simultaneously generating coherent written content. This finding aligns with Cognitive Load Theory (CLT) (Paas et al, 2003; Sweller, 1988), which posits that working memory has a limited capacity, and learning tasks that exceed this capacity can hinder performance.

CLT, originally developed by Sweller (1988), posits that working memory has a limited capacity and that learning effectiveness is influenced by how cognitive resources are allocated during a task. According to CLT, intrinsic cognitive load stems from the inherent complexity of the material, while extraneous load arises from how the task is structured or presented (Sweller, 1994; Paas, Renkl, & Sweller, 2003).

In the context of digital writing, extraneous load may increase due to the need to navigate a keyboard, monitor the screen, and maintain syntactic coherence—all of which may interfere with content generation and reduce cognitive efficiency. Studies such as those by Chandler and Sweller (1991) and more recently by van Merriënboer and Sweller (2010) emphasize that high extraneous load can lead to cognitive overload, limiting the learner's ability to process information effectively. Our findings suggest that digital writing, while efficient in certain contexts, may impose additional cognitive burdens that compete with higher-order cognitive processes, particularly in individuals more sensitive to motor-cognitive multitasking.

The neuroeducational markers reveal a complex interaction between writing modality and cognitive engagement. While digital writing generally increased attention levels (particularly in male participants, from 41% to 51%), it simultaneously reduced emotional engagement. This trade-off between cognitive focus and emotional connection raises important questions about the optimal choice of writing modality for different educational objectives.

In conclusion, our findings contribute to a more nuanced understanding of how writing modalities interact with individual characteristics to influence cognitive processing. The clear gender differences in neural activation patterns, combined with the distinct cognitive and emotional profiles associated with each writing modality, suggest the need for more personalized approaches to writing instruction in higher education. These insights provide a neurophysiological basis for developing evidence-based strategies that optimize learning outcomes while considering individual differences in cognitive processing.

Conclusion

The results of this research provide robust empirical evidence of fundamental neurological differences between manual and digital writing, as well as between genders, in university students. These findings have important theoretical and pedagogical implications. First, writing modality significantly influences brain activation patterns: handwriting elicits more holistic and emotionally engaged neural activity—especially evident in the bilateral activation observed in female participants—while digital writing fosters more structured, focused, and working memory-intensive processing. These modality-specific patterns suggest that handwriting may enhance creativity, emotional expression, and integrated cognitive processing, whereas digital writing may promote efficiency, attentional focus, and syntactic precision. The observed differences suggest that each writing modality may be more appropriate depending on the nature and purpose of the task. Handwriting appears to be especially suitable for activities that require personal expression and creativity, as well as for tasks that benefit from greater emotional integration and deeper, multifaceted cognitive processing. In contrast, digital writing seems better aligned with tasks that demand precision, efficiency, and intensive visual monitoring—conditions under which a more structured and less emotionally involved cognitive style may be advantageous. These findings carry important implications for educational practice. They highlight the need to move beyond a purely utilitarian perspective when selecting writing modalities, taking into account not only practical factors such as speed or accessibility, but also the cognitive and emotional demands inherent to the task. Tailoring the writing modality to the learning objective may enhance both engagement and academic performance, particularly in higher education contexts where writing is a central tool for learning and expression.

The neurophysiological differences observed between male and female participants suggest that each gender may benefit from distinct educational strategies when engaging in writing tasks. For male students, digital writing appears to enhance attentional focus and task engagement, while handwriting may facilitate more automated and less stressful processing. This pattern indicates that educational tasks might be more effective for males when designed with sequential, focused processing in mind. In contrast, female students demonstrated more bilateral brain activation and stronger emotional engagement, particularly during handwriting. This suggests that handwriting may be especially beneficial for tasks requiring self-expression, emotional integration, and creative thought. Digital writing, meanwhile, may still support precision and organization, aligning with tasks that demand structured output. Designing activities that leverage female students' integrated and multifaceted cognitive processing may enhance their learning outcomes.

These findings support the implementation of differentiated pedagogical approaches that recognize and accommodate individual and gender-based cognitive styles. Educational strategies should not adopt a one-size-fits-all model but instead offer students varied opportunities to engage with both handwriting and digital writing modalities. By aligning instructional methods with the neurocognitive profiles of learners, educators can enhance not only academic performance but also cognitive engagement, emotional connection, and self-regulation during writing activities.

These gender-based patterns also raise important questions about the extent to which such differences are shaped by biological predispositions versus early educational experiences and socialization. Future studies could explore whether differential exposure to handwriting and digital writing in early schooling influences the development of distinct neural pathways. Understanding these dynamics may help educators design interventions that promote balanced cognitive engagement across genders and inform more equitable pedagogical practices. Moreover, gender differences in neural engagement emerged as a critical factor. Male participants displayed more lateralized and automated activation during handwriting, shifting to more cognitively demanding patterns during digital tasks. In contrast, female participants consistently exhibited bilateral activation, particularly during handwriting, accompanied by greater emotional involvement. These results align with previous neuroimaging findings on sex-based differences in language and motor processing (Garn et al., 2009; Ruigrok et al., 2014; Shaywitz et al., 1995), but go further by integrating neuroeducational markers such as attention, stress, and engagement. These findings have significant implications for educational practice in higher education. The clear differences in neural activation patterns suggest that a one-size-fits-all approach to writing modalities may be suboptimal. Instead, educators might consider tailoring writing assignments based on both the intended learning outcomes and individual student characteristics, including gender. For example, tasks requiring emotional reflection or creativity might benefit from handwritten formats, while structured analytical tasks may be better suited to digital writing. Educational programs could also include training to help students become aware of their cognitive and emotional responses to different modalities, thus promoting metacognitive awareness and self-regulated learning.

However, several limitations must be acknowledged. The small sample size (n = 10) limits the generalizability of the findings and calls for caution when extrapolating results to broader populations. The sample was also limited to right-handed university students in a single academic program, which may not capture variability across disciplines, handedness, or developmental stages. Additionally, the controlled laboratory conditions, while essential for EEG precision, may not reflect authentic academic writing contexts.

Future research should expand sample size and diversity, incorporating participants from different age groups, educational levels, and sociocultural backgrounds. Longitudinal studies could examine how repeated use of writing modalities affects neural plasticity and academic performance over time. Moreover, future work could investigate how different writing tasks—such as narrative writing, argumentative essays, or technical reports—interact with neural activation patterns, emotional engagement, and learning outcomes. Incorporating multimodal neuroimaging techniques and behavioral data could further enrich our understanding of how writing shapes cognition in the digital age. Another methodological limitation concerns the use of the PRONIN© and SIEN© protocols. Although they represent an innovative framework for analyzing brain activity and neuroeducational markers, their applicability across different educational contexts and populations remains limited. Further validation of these tools is needed to strengthen their reliability and generalizability in future neuroeducational research. Despite the relevance of the findings, certain limitations should be acknowledged. The small and homogeneous sample—comprising ten right-handed university students from a single academic program—limits the generalizability of the results to broader and more diverse populations. Furthermore, the controlled laboratory environment, while essential for EEG precision, does not fully reflect the ecological conditions of academic writing in real-world contexts. Future research should consider expanding the sample to include diverse age groups, academic disciplines, and handedness profiles, and adopt longitudinal designs to explore the evolution of neural patterns over time. Additionally, comparing different types of writing tasks—such as reflective, narrative, or analytical writing—could yield further insights into how writing modality interacts with cognitive and emotional demands, informing more nuanced pedagogical strategies.

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