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Complex Approaches to Handedness and Brain
Lateralization

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DEDICATÓRIA

Quando meu pai viu que eu passei na graduação em física na UFBA, minha mãe o encontrou chorando no quarto, quebrando o cofrinho e disposto a mandar seu filho de 17 anos para uma cidade grande, vivendo em repúblicas estudantis em uma cidade longe da família. Disse que eu deveria investir tudo que tenho porque não queria que eu passasse o resto da vida em trabalhos informais e tendo paixão pela pesquisa científica. Portanto, dedico este trabalho a quem sempre me deu suporte, não julgando se o que eu iria fazer me traria dinheiro ou status, apenas querendo que eu fosse feliz: **Meus pais, Adriano e Luciana**. Este trabalho é fruto de anos de aprendizagem científica e dedicação em uma área puramente acadêmica, que não é comum na cidade de onde eu venho e na minha família, sendo o primeiro da minha família a entrar numa universidade federal e a realizar um mestrado. Nada disso seria possível sem que meus pais acreditassem no meu potencial pesquisador e investigativo, mesmo quando eu não acreditei. E se estou finalizando este trabalho é por honra e amor dos meus pais que deram tudo que tinha para que eu estivesse aqui, mesmo em situações extremas me incentivaram a continuar minha carreira acadêmica . Hoje meu pai está melhor e segue em tratamento.

DEDICATORY

When my father found out I had been accepted into the undergraduate physics program at UFBA, my mother found him crying in the bedroom, breaking open his piggy bank and determined to send his 17-year-old son to a big city, to live in student housing far from our family. He told me I should invest everything I had, because he didn't want me to spend the my life in informal jobs while holding onto a passion for scientific research. Therefore, I dedicate this work to those who always supported me, never judging whether what I chose to do would bring money or status, only wanting me to be happy: **my parents, Adriano and Luciana**. This work is the result of years of scientific learning and dedication to a purely academic field, one that is uncommon in the city I come from and in my family. I am the first in my family to attend a federal university and to pursue a master's degree. None of this would have been possible without my parents believing in my potential as a researcher and investigator, even when I didn't believe in myself. During my master's program, my father was diagnosed with a cancer and spent months in the ICU. If I'm now completing this work, it is out of honor and love for my parents, who gave everything they had so I could be here. Even in the most extreme circumstances, they encouraged me to continue my academic journey. Today, my father is doing better and continues his treatment.

PREFÁCIO

Este trabalho é, antes de tudo, fruto de uma longa travessia experimental e fenomenológica. Embora a coleta de dados e as análises sobre EEG e captura de movimento tenham se concentrado no período do meu mestrado, iniciado em 2023, suas raízes remontam a um caminho iniciado ainda em 2020. Naquele ano, comecei a estudar a sincronização de medidas de movimento no contexto da improvisação em dança, sob orientação dos professores Ivani Santana (UFRJ) e José Garcia (UFBA). Esse primeiro contato com a biomecânica me proporcionou o aprendizado necessário para manipular dados e utilizar ferramentas que hoje sustentam a base deste trabalho.

Durante aquelas investigações iniciais, percebi que a improvisação era frequentemente conduzida por uma das mãos – geralmente a dominante. Essa observação me levou a iniciar uma colaboração com Mariana Teixeira, que também havia notado assimetrias no movimento durante a caminhada. Juntos, durante a pandemia da COVID-19, realizamos diversos experimentos caseiros com familiares como voluntários e ferramentas improvisadas de tracking de vídeo. Ainda que movidos pelo entusiasmo de "querer medir tudo", esses experimentos não podiam, à época, se transformar em uma pesquisa formal – o comitê de ética ainda não permitia novas coletas com seres humanos devido à pandemia do COVID-19.

Foi nesse período que o projeto ganhou maturidade. Começamos a pensar na lateralização não apenas de forma quantitativa, mas também clínica, epistemológica e fenomenológica. Reunimos-nos com professores como Flora Bacelar (UFBA), com quem dialogamos sobre modelos ecológicos da lateralidade, e Guilherme Brodt (UCS), entre outros. Mas foi no LABIOS, sob a orientação do professor José Garcia, que o projeto encontrou uma base sólida. Ainda no terceiro semestre da graduação em Física, fomos acolhidos por esse grupo e encorajados a seguir com uma ideia que ainda era embrionária, mas já revelava diferenças motoras entre as mãos.

Em 2022, com o apoio da professora Cecília Accioly, o projeto se oficializou como uma iniciação científica com o objetivo de integrar neurociência e biomecânica. Foi com entusiasmo que reencontrei a possibilidade de dar continuidade à pesquisa que eu e Mariana havíamos

começado em casa, mas agora com uma abordagem mais robusta: encontros presenciais, equipamentos padronizados e metodologias inspiradas na análise de comportamentos neuromotores.

Ao final da iniciação científica, desenvolvi o protocolo de coleta e o submeti ao comitê de ética – aprovação que só viria já no contexto do mestrado, sob a orientação do professor José Garcia. Durante o mestrado, meu entusiasmo por entender as múltiplas facetas da lateralidade manual me levou a dialogar com pesquisadores como Jean-François (Rutgers University) e Fernanda Matias (UFAL), cujas contribuições foram fundamentais para o refinamento conceitual e metodológico deste estudo.

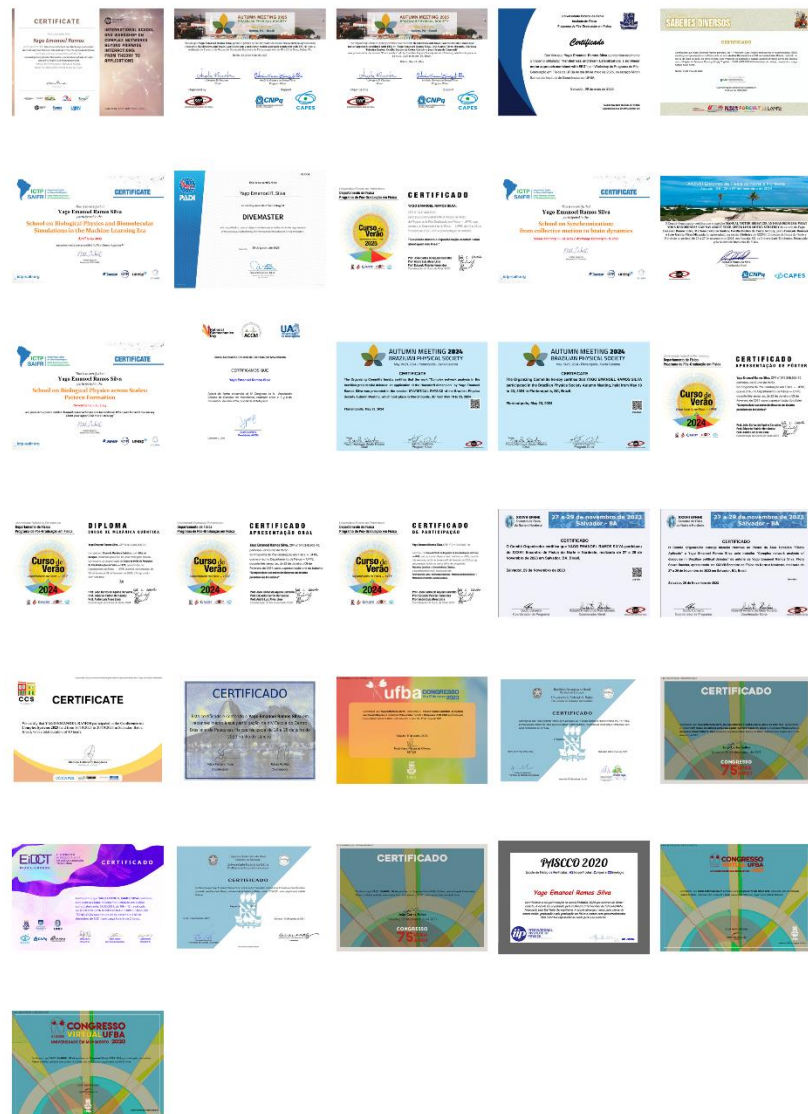
Este trabalho é o resultado de um esforço interdisciplinar e colaborativo. Agradeço profundamente ao professor José Garcia, que desde o início acreditou e acolheu esta pesquisa, viabilizando os experimentos e, não raramente, transportando equipamentos de EEG pelo campus. À professora Cecília Accioly, por seu apoio constante, pela coorientação generosa e pela disponibilização da sala de captura de movimento (MOCAP) da Escola de Dança – bem como por ceder seu espaço pessoal para o armazenamento dos equipamentos. Ao professor Raphael Rosário, que gentilmente me ofereceu caronas com os equipamentos em mãos, facilitando diversas coletas.

Agradeço também aos estudantes do LABIOS, especialmente Iago, Átila, Flávio, Marcicleine e Dhyego (este último mais focado na parte de EEG), pelo auxílio essencial na organização e execução dos experimentos. Cuidar do setup, garantir sua limpeza e estabilidade foi um trabalho que muitas vezes é invisível e é profundamente fundamental.

Por fim, agradeço aos voluntários que participaram da pesquisa, dedicando tempo, corpo e interesse para tornar esta investigação possível. A todos que contribuíram para minha formação como cientista da complexidade e pesquisador do comportamento neuromotor: minha mais sincera gratidão. Agradeço também ao Programa de Pós-Graduação em Física, que conta com funcionários incríveis e solícitos: Marcos Paulo, Marcos Souza e Suani Pinho. Facilitaram muitos dos processos burocráticos ao longo desta jornada e me ajudaram a conseguir auxílios para muitas viagens acadêmicas de minicursos, congressos, escolas. Esses eventos foram

cruciais para o meu crescimento como pesquisador, tendo sido premiado em duas ocasiões (Encontro do Norte e Nordeste 2023 e Encontro de Outono da SBF 2025) com o prêmio de melhor pôster.

Sou igualmente grato à CAPES pelo apoio financeiro por meio da concessão da bolsa de mestrado, sem a qual este trabalho não teria sido possível.



Meus certificados

PREFACE

This work is, above all, the result of a long experimental and phenomenological journey. Although the data collection and the analyses of EEG and motion capture focused mainly during my master's studies, which began in 2023, the roots of this research reach back much further. In 2020, I began exploring movement synchronization in the context of dance improvisation, under the guidance of professors Ivani Santana (UFRJ) and José Garcia (UFBA). This initial contact with biomechanics allowed me to develop the skills needed to handle data and apply many of the tools that now form the basis of this work.

During those early investigations, I noticed that improvisation was often guided by one hand, usually the dominant one. This observation led me to collaborate with Mariana Teixeira, who had also hypothesized that people tend to swing one arm more than the other while walking. Together, during the COVID-19 pandemic, we conducted several home-based experiments using family members as participants and video tracking tools. At the time, these experiments couldn't yet become formal research: our enthusiasm for "measuring everything" clashed with the ethics committee's restrictions on human data collection due to the pandemic.

That context, however, helped the project mature. We began considering laterality not only through a quantitative lens but also from clinical, epistemological, and phenomenological perspectives. We held meetings with scholars like Flora Bacelar (UFBA), who helped us conceptualize ecologic lateral models, and Guilherme Brodt (UCS), among others. Yet it was within the LABIOS lab, under Professor José Garcia's mentorship, that the project found a solid foundation. At that point, we were only in our third semester of the undergraduate physics program, the research was still very preliminary, but it already suggested that certain movements were markedly better performed with one hand over the other.

In 2022, with the support of Professor Cecília Accioly, the project took official form through a scientific initiation grant aimed at unifying neuroscience and biomechanics. I was thrilled to have the opportunity to continue the work Mariana and I had started at home, but this time with a more structured approach: weekly in-person meetings, standardized measurement equipment, and neuromotor approaches to analyze lateral behaviors.

At the end of the scientific initiation phase, I developed a formal research protocol and submitted it to the ethics committee, a process that was only approved during my master's under Professor José Garcia's supervision. Throughout the master's program, I remained enthusiastic about investigating manual laterality, meeting with researchers in neural and motor behavior such as Jean-François (Rutgers University) and Fernanda Matias (UFAL), whose insights substantially shaped the final form of this research.

This work is the result of interdisciplinary collaboration. I am deeply grateful to Professor José Garcia, who continuously supported this project and enabled experimental procedures, often involving transporting EEG equipment across campus. I thank Professor Cecília Accioly for her generous co-supervision and for making the motion capture room (MOCAP) at the School of Dance available, including offering her personal office as a space to store research materials. I am also thankful to Professor Raphael Rosário, who often gave me rides to help move EEG equipment to the data collection site.

I would also like to thank the LABIOS students, especially Iago, Átila, Flávio, Marcicleine, and Dhyego (who was particularly interested in the EEG part), for their essential help in organizing and maintaining the experimental setup. Their work, often invisible but absolutely fundamental, ensured that the experiments were properly executed.

Finally, I thank all the volunteers who generously offered their time and energy to participate in this research. To everyone who contributed to my development as a complexity scientist and a neuromotor behavior researcher: my most sincere gratitude. I would also like to thank the Graduate Program in Physics, whose dedicated staff, Marcos Paulo, Marcos Souza, and Suani Pinho, greatly facilitated many of the bureaucratic processes throughout this journey and helped me obtain grants for many academic trips for short courses, conferences, and schools. These events were crucial for my growth as a researcher, having been awarded on two occasions (Encontro do Norte e Nordeste 2023 and Autumn Meeting 2025) with the award for best poster presentation.

I am also grateful to CAPES for providing the master's scholarship, without which this work would not have been possible.

EPIGRAPH

This work is the result of a genuine effort to unify diverse scientific perspectives, integrating knowledge from biological sciences, socio-behavioral sciences, neuroscience, and studies on optimization and energy efficiency. These approaches converge through interdisciplinary lenses based on physical quantities, originally used to study ideal gases, frictionless spherical objects, among other simple systems. Nowadays, such concepts can be applied in broader interdisciplinary contexts and use it to study ourselves, thanks to complexity theories.

“Il faut relier les savoirs, dépasser les frontières disciplinaires pour appréhender la complexité du réel.”

(“We must connect knowledge and go beyond disciplinary boundaries to understand the complexity of reality.”)

— Edgar Morin

“Science cannot solve the ultimate mystery of nature. And that is because, in the last analysis, we ourselves are part of nature and, therefore, part of the mystery that we are trying to solve.”

— Max Planck

ABSTRACT

The evolutionary history of the human species reveals a marked progression in brain and upper limb lateralization within the *Homo* genus. Particularly for tool use and fire control, *Homo sapiens* evolved with increasingly refined motor abilities, culminating in a strong preference for a dominant hand. Contrary to the common belief that asymmetry may indicate inefficiency or inadaptability, manual lateralization in humans reflects a form of specialization—similar to patterns observed in apex predators—where specialization often confers adaptive advantages. The experience of left-handed individuals in predominantly right-handed societies underscores the need to better understand motor behavior and the mechanisms underlying hand dominance. This experimental study employs a combination of biomechanical metrics and EEG-based measurements to analyze general motor behavior during fine motor tasks performed with both hands, specifically handwriting. It further explores how these behaviors evolve over time, with a focus on the emergent dynamics given by permutation entropy measures. Our findings reveal that right-handed exhibit more optimized and stable motor strategies across hands, whereas left-handers and ambidextrous individuals display greater variability and less consistent dominance patterns. However, temporal analyses using permutation entropy of motor behavior revealed similar lateralization profiles between left- and right-handed groups, suggesting functional equivalence in hand use. EEG analyses indicated that right-handers individuals show more distributed and temporally non-linear brain behavior, potentially due to reduced experience or training with the non-dominant hand in daily tasks. We conclude that human lateralization supports a variety of neuromotor configurations and those behavioral patterns are shaped more by usage habits and experience than by intrinsic differences between handedness groups. These findings highlight the evolutionary and functional relevance of motor lateralization in *Homo sapiens*.

Keywords: Complexity, Permutation Entropy, Handedness, Brain Lateralization, Motor Control, Evolutionary Biology.

RESUMO

A história evolutiva da espécie humana revela uma progressão marcante na lateralização cerebral e dos membros superiores dentro do gênero *Homo*. Em especial, para o uso de ferramentas e o controle do fogo, *Homo sapiens* evoluiu com habilidades motoras cada vez mais refinadas, culminando em uma forte preferência por uma mão dominante. Contrariando a crença comum de que a assimetria indicaria ineficiência ou falta de adaptação, a lateralização manual em humanos reflete uma forma de especialização, semelhante aos padrões observados em superpredadores, nos quais a especialização frequentemente confere vantagens adaptativas. A experiência de indivíduos canhotos em sociedades predominantemente destros ressalta a importância de compreender melhor o comportamento motor e os mecanismos que fundamentam a dominância manual. Este estudo experimental utiliza uma combinação de métricas biomecânicas e medidas baseadas em EEG para analisar o comportamento motor geral durante a execução de tarefas motoras finas com ambas as mãos, especificamente a escrita manual. Além disso, investiga como esses comportamentos evoluem ao longo do tempo, com foco na dinâmica emergente capturada por medidas de entropia de permutação. Nossos resultados revelam que indivíduos destros apresentam estratégias motoras mais otimizadas e estáveis entre as mãos, enquanto canhotos e ambidestros demonstram maior variabilidade e padrões de dominância menos consistentes. No entanto, análises temporais do comportamento motor utilizando entropia de permutação indicaram perfis de lateralização semelhantes entre os grupos de canhotos e destros, sugerindo uma equivalência funcional no uso das mãos. As análises de EEG indicaram que indivíduos destros apresentam padrões cerebrais mais distribuídos e não lineares ao longo do tempo, possivelmente devido à menor experiência ou treinamento com a mão não dominante nas tarefas cotidianas. Concluimos que a lateralização humana permite uma variedade de configurações neuromotoras, e que os padrões comportamentais são moldados mais pelos hábitos de uso e pela experiência do que por diferenças intrínsecas entre os grupos de dominância manual. Esses achados ressaltam a relevância evolutiva e funcional da lateralização motora em *Homo sapiens*.

Palavras-chave: Complexidade, Entropia de Permutação, Lateralidade, Lateralização Cerebral, Controle Motor, Biologia Evolutiva.

RESUMEN

La historia evolutiva de la especie humana revela una marcada progresión en la lateralización cerebral y de las extremidades superiores dentro del género *Homo*. En particular, para el uso de herramientas y el control del fuego, *Homo sapiens* evolucionó desarrollando habilidades motoras cada vez más refinadas, culminando en una fuerte preferencia por una mano dominante. Contrario a la creencia común de que la asimetría podría indicar ineficiencia o falta de adaptabilidad, la lateralización manual en los humanos refleja una forma de especialización, similar a los patrones observados en depredadores tope, donde la especialización suele conferir ventajas adaptativas. La experiencia de los individuos zurdos en sociedades predominantemente diestras subraya la necesidad de comprender mejor el comportamiento motor y los mecanismos que sustentan la dominancia manual. Este estudio experimental emplea una combinación de métricas biomecánicas y medidas basadas en EEG para analizar el comportamiento motor general durante la ejecución de tareas motoras finas con ambas manos, específicamente la escritura manual. Además, explora cómo estos comportamientos evolucionan con el tiempo, con un enfoque en la dinámica emergente capturada a través de medidas de entropía por permutación. Nuestros hallazgos revelan que los individuos diestros exhiben estrategias motoras más optimizadas y estables entre las manos, mientras que los zurdos y ambidiestros muestran una mayor variabilidad y patrones de dominancia menos consistentes. Sin embargo, los análisis temporales del comportamiento motor mediante entropía de permutación revelaron perfiles de lateralización similares entre los grupos de diestros y zurdos, lo que sugiere una equivalencia funcional en el uso de las manos. Los análisis de EEG indicaron que los individuos diestros presentan patrones cerebrales más distribuidos y no lineales en el tiempo, posiblemente debido a una menor experiencia o entrenamiento con la mano no dominante en las actividades cotidianas. Concluimos que la lateralización humana permite una amplia variedad de configuraciones neuromotoras, y que los patrones de comportamiento están más influenciados por los hábitos de uso y la experiencia que por diferencias intrínsecas entre los grupos de dominancia. Estos hallazgos resaltan la relevancia evolutiva y funcional de la lateralización motora en *Homo sapiens*.

Palabras clave: Complejidad, Entropía de Permutación, Lateralidad Cerebral, Control Motor, Biología Evolutiva.

LIST OF ABBREVIATIONS AND ACRONYMS

DH	Dominant hand	FR	Right frontal lobe
NDH	Non dominant hand	FL	Left frontal lobe
LH	Left-handed	CR	Right central lobe
RH	Right-handed	CL	Left central lobe
WR	Writing	TR	Right temporal lobe
PE	Permutation Entropy	TL	Left temporal lobe
RMS	Root Mean Square	PR	Right parietal lobe
DR	Drawing	PL	Left parietal lobe
WR-DH	Writing with dominant hand	OR	Right occipital lobe
WR-NDH	Writing with non-dominant hand	OL	Left occipital lobe
DR-DH	Drawing with dominant hand	ERDS	Event related desynchronization/synchronization
DR-NDH	Drawing with non-dominant hand	MED	Movement element decomposition

DH	Dominant hand	FR	Right frontal lobe
EEG	Electroencephalography	TVG	Time Variant Graph
Qeeg	Quantitative electroencephalography		

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1. INTRODUCTION

In this work, we explore hand dominance and brain lateralization processes using experimental approaches to classify human motor control behavior, unifying data of left-handed, ambidextrous and right-handed subjects.

1.1. Handedness evolutionary history

Hand dominance is a fundamental aspect for understanding biological movement. Over the course of millions of years, *Homo sapiens* evolved as a species highly specialized in tool use and fine motor skills, a key trait that contributed to our evolutionary success on Earth. Our motor abilities have been shaped by a long evolutionary process, yet a striking characteristic remains: although we are biologically optimized for manipulating objects, most individuals consistently prefer to use only one hand. Approximately 90% of the global population exhibits right-hand dominance (McManus, 1992; Papadatou-Pastou et al., 2020).

This pattern of manual lateralization is not unique to humans. Similar tendencies have been observed in other primates, particularly those that occupy terrestrial ecological niches. Caspar et al. (2022) demonstrated that terrestrial primates exhibit stronger lateralization compared to arboreal species, with humans showing the highest level of hand preference (see Figure 1.1). This suggests that hand dominance may be linked to environmental and functional demands associated with terrestrial locomotion and tool use, potentially offering an evolutionary advantage by allowing for greater motor efficiency and specialization (Russell et al., 2011; Meguerditchian et al., 2013).

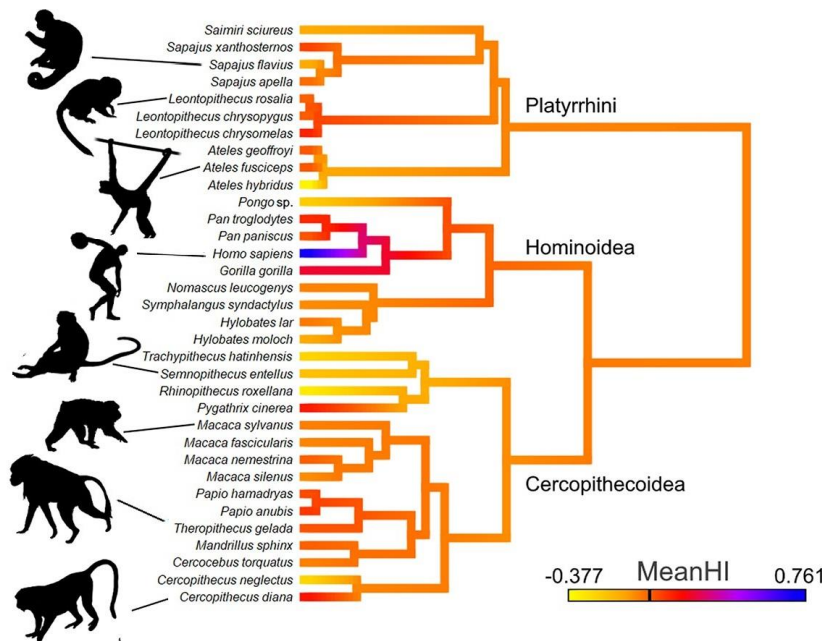


Figure 1.1: Phylogenetic tree of *Homo sapiens* highlighting the Mean Handeness Index (MeanHI): $(R-L)/(R+L)$, where R and L are the number of times that individuals used right and left hand, respectively, to reach food in a tube (tube task) on average by specie. Figure by Caspar et al. (2022).

Handedness can be understood as an evolutionary legacy rooted in primitive functional asymmetries between the right and left sides of the body. This biological asymmetry is not unique to humans, but rather a widespread phenomenon observed across the tree of life—from bacteria to whales (Clapham, 1995; Milenković, 2007; Milenković et al., 2016). At the neuromotor level, patterns of lateralization have been documented in a variety of species, including dogs, rats, chimpanzees, birds, lizards, and even fish (Milenković et al., 2016; Engbretson et al., 1981; Hunt et al., 2001; Nottebohm et al., 1976; Wells, 2002; Hopkins et al., 2001; Elalmis et al., 2003).

Contrary to the intuitive assumption that symmetry might offer evolutionary advantages, the trajectory of human evolution suggests the opposite: lateralization has increased over time. Individuals with more symmetrical motor behavior were not favored by natural selection within the *Homo* lineage. Instead, asymmetrical motor specialization—such as dominant hand use—may have enhanced efficiency in tool use and coordination, conferring selective advantages in increasingly complex environments (Corballis, 2009; Fagard, 2013).

A major challenge in disciplines concerned with understanding human movement—such as robotics—is how to accurately replicate it. To design systems that achieve motor optimization, it is essential to understand the process of lateralization in primates. If a robot were to be highly optimized for manipulation, should it also exhibit a preferred hand? As pointed out by researchers since Darwin (1859), natural selection occurs in scenarios of competition and resource scarcity. In this context, lateralization may represent an adaptive advantage by enabling hemispheric specialization (Güntürkün et al., 2020; Rogers, 2002). Therefore, lateralization in robots would make sense especially in environments with limited resources, where efficiency and energy conservation are crucial.

Although the dominant hand is generally associated with greater dexterity and precision, the non-dominant hand plays a crucial role in bimanual coordination and tool use. Sainburg (2014) proposes a hybrid model of motor control in which the non-dominant hand is primarily responsible for impedance control, stabilizing objects, or providing resistance during fine motor tasks. A common example of this is holding a loaf of bread steady with one hand while cutting it with the other. This stabilizing action is essential for the successful execution of complex movements and tool use.

These findings suggest that evolution has not merely favored the efficiency of one side of the body, but rather promoted a functional specialization between the limbs. Each hand contributes uniquely to the performance of skilled actions: the dominant hand executes dynamic and precise tasks, while the non-dominant hand provides support, stabilization, and spatial referencing (Guiard, 1987; Sainburg, 2002; Sainburg, 2014). Such complementary division of labor may reflect an evolutionary optimization strategy rather than a simple case of unilateral enhancement.

From an evolutionary perspective, object manipulation and fine motor skills primarily served predatory functions, such as crafting stone tools for hunting, processing meat, and self-defense (Muller et al., 2022) (see Figure 1.2). Even the manipulation of fire requires a high degree of motor specialization, therefore the ability to manipulate fire arose after the ability to manipulate tools Wrangham (2009) (see Figure 1.3), which was essential for our ancestors to develop the ability to cook food. According to Herculano-Houzel (2017), this advancement played a crucial

role in enabling the evolutionary expansion of the human brain and development of our cognitive functions. This behavior can be compared to ecological strategies found among predators in biology, particularly the distinction between generalist and specialist predators.



Figure 1.2: Stone based weapons created and used by primitives *Homo* genre individuals: a: Knapping footage; b: Discoidal core and flakes; c: Earlier (left) and later (right) handaxes; d: Preferential Levallois core and flake; e: Recurrent Levallois core and flakes; f and g: Prismatic blade cores and blades. Figure by Muller et al., (2022).

While manual lateralization (handedness) has undergone an evolutionary process of specialization in the human species, the lateralization of other body parts does not follow the same pattern. The classic work by Porac & Coren (1981) argues that only about 50% of the population exhibits lateral dominance of the eye, ear, foot, and hand all on the same side. This suggests that human lateralization is inherently manual in nature. Such findings reinforce the idea that hand specialization is closely linked to our evolutionary development, particularly because it enhances tool use, an ability that becomes increasingly prominent as we move closer to modern times along the timeline shown in Figure 1.3.

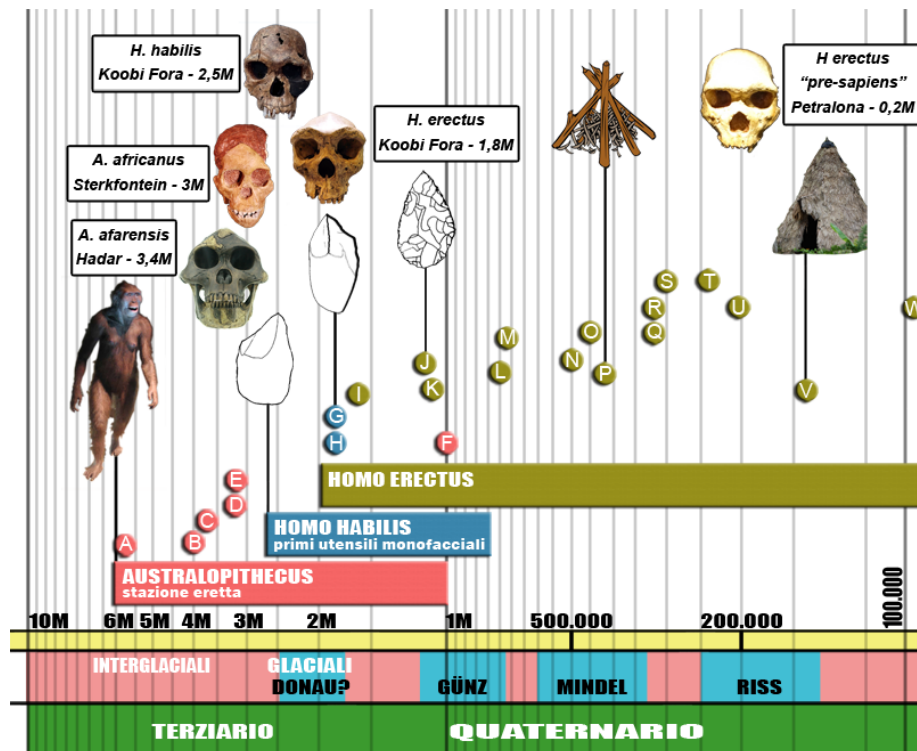


Figure 1.3: Evolutionary history of the genus *Homo*: A: Lukeino, Lothogam; B: Afarensis, Hadar (Ethiopia); C: Afarensis ("Lucy"), Hadar (Ethiopia); D: Africanus; E: Robustus; F: Last Australopithecines; G: Oldoway Industry (Tanzania); H: First structured settlements, Melka Kunturé (Ethiopia); I: *Homo erectus* in Europe; J: Start of the Acheulean industry in Africa; K: *Homo erectus* in France; L: Start of the Acheulean industry in Europe; M: *Homo erectus* in Germany; N: Java Man; O: Tautavel Man (France); P: Fire domain: Nice (France); Vértesszöllös (Hungary); Q: Hunting techniques, Torralba del Moral (Spain); R: Sinanthropus (Peking Man), Zhoukoudian (China); S: Pre-Neanderthal fossils from Swanscombe (Great Britain); T: Pre-Neanderthal fossils from Petralona (Greece); U: Pre-Neanderthal fossils from Steinheim (Germany); V: Hut, Nice (France); W: *Homo erectus*, Gerona (Spain). [Figure source: [https://commons.wikimedia.org/wiki/File:Evoluzione_umana_\(1M-100.000_anni_fa\).png](https://commons.wikimedia.org/wiki/File:Evoluzione_umana_(1M-100.000_anni_fa).png)]

Generalist predators can exploit a wide range of prey or resources. In contrast, apex predators (or superpredators) occupy the top of the food chain not necessarily because they are the strongest, but because they exhibit refined adaptations that allow them to hunt specific prey with extreme efficiency. Schreiber (1997) proposed a theoretical ecological model that shows an advantage for specialist predators in keeping balance between competitive prey. A classic example is the cheetah (*Acinonyx jubatus*), which—despite coexisting with stronger carnivores such as lions and leopards—thrives as a top predator due to its specialization in high-speed hunting of gazelles (Hayward & Slotow, 2009).

This analogy suggests that *Homo sapiens* can also be viewed as a superpredator—not merely because of physical strength, but due to the exceptional ability to manipulate tools and the

environment. In this context, manual lateralization—the functional specialization between the right and left hands—can be seen as an adaptive refinement. Having one hand specialized for precision tasks (such as tool use or cutting) and the other for support may have provided a significant evolutionary advantage.

While symmetrical manual skill (true ambidexterity) might appear advantageous at first glance, evidence from nature shows that superpredatory behavior is typically associated with specialization (Estes et al., 2011; Michálek et al., 2017). Thus, the evolution of lateralized hand use may have played a crucial role in the emergence of *Homo sapiens* as a top predator with highly refined motor control.

While the functional specialization of the hands during task execution appears to have a well-established explanation, the reason why the vast majority of humans exhibit right-hand dominance remains unclear. Equally uncertain is what fundamentally distinguishes left-handed individuals at the neuromotor level. The phenomenon is not entirely straightforward in non-human primates either. For instance, Olson et al. (1990) found that while gorillas tend to favor the right hand, gibbons show a preference for the left, highlighting the complexity of lateralization patterns even within the primate order.

The primary objective of this study is to investigate the neuromotor profiles of right-handed, ambidextrous and left-handed individuals. By adopting a comparative approach, this research aims to explore the sensorimotor behaviors of both left-handed and ambidextrous individuals—who represent the exception within the most lateralized species on Earth. Understanding these atypical patterns of motor control may shed light on the evolutionary, developmental, and neurological foundations of handedness.

1.2. Left-handers in humankind

Historically, left-handedness has been misunderstood and often stigmatized, with social attitudes toward left-handers reflecting broader cultural values and misconceptions. Ancient societies associated the left hand with impurity and misfortune, and religious practices in Western and Middle Eastern cultures often reserved the left hand for tasks considered "unclean." Such views were deeply embedded in cultural lexicons: the Latin root for "sinister"

meant “left” and carried connotations of error and malevolence, which reinforced negative stereotypes of left-handed people as unlucky or untrustworthy, (Guenther, 2018).

Medicine has also played a role in shaping the treatment of left-handers, historically promoting "corrections" for left-handed children. In the 19th and 20th centuries, many schools and medical practitioners encouraged or even forced left-handers to switch to their right hand, believing that such "retraining" would prevent developmental or cognitive issues (Wolman, 2005). This practice often led to unintended consequences, including increased rates of stuttering and other speech difficulties, as documented by psychiatrist I. Kushner, who highlighted the harmful effects of forced hand-switching and the subsequent "tying of tongues.", (Harris, 2012). Left-handed individuals who underwent such retraining sometimes experienced physical and psychological challenges, and some developed speech impediments that were only resolved once they returned to using their dominant hand.

In modern times, the challenges faced by left-handed individuals are of a different nature. In a world filled with specialized tools designed predominantly for right-handed use, such as scissors, computer mice, pliers, and even the orientation of door handles, left-handers often encounter daily inconveniences (Beaton, 2012). In Brazil, especially, many left-handed individuals were pressured during childhood to use their right hand instead of their left hand, as left-handedness was historically perceived as a defect or undesirable trait (Costa, 2023).

These social experiences can significantly influence patterns of hand dominance, potentially modifying natural motor patterns. Consequently, such environmental and cultural pressures may bias research findings that report stronger lateralization in right-handers during motor tasks (Papadatou-Pastou et al., 2020). It is therefore essential to consider sociocultural factors when interpreting data on handedness.

Social factors do not always disadvantage left-handers in motor activities. In fact, research suggests that left-handers may have a performance advantage in sports due to their relative rarity and less predictable play patterns (see Figure 1.4). According to Raymond et al. (1996), this rarity makes left-handed athletes less predictable to opponents who are more accustomed to facing right-handers. Loffing et al. (2010) found that left-handed tennis players tend to have

a competitive edge, particularly at lower levels of play where opponents have had less exposure to left-handed competitors. This difference in pattern consistence may be attributed to social factors, where left-handers have been more frequently exposed to situations that required them to develop their own adaptations in order to function in a world designed for right-handers.



Figure 1.4: A volleyball player performing a jump serve: a) Left-handed [Figure source: <https://commons.m.wikimedia.org/wiki/File:5a1d745891.jpeg>]; b) Right-handed [Figure source: https://commons.wikimedia.org/wiki/File:Volleyball_Jump_Serve-pjt.jpg].

These findings support the idea that, while there is no definitive biological explanation for the persistence of left-handedness in the population, it may represent an evolutionary adaptation related to intraspecific competition, that is, a strategic advantage in competitive interactions among members of the same species. This hypothesis aligns with the theory of negative frequency-dependent selection, where traits that are rare in a population can confer advantages simply because they are unexpected (Faurie & Raymond, 2005). Additional studies, such as Brooks et al. (2004), have shown that left-handed athletes are overrepresented in interactive sports like fencing and boxing, further supporting the notion that left-handedness can offer a context-specific evolutionary benefit.

1.3. Experimental and data analysis principles: urgency of complexity approaches

Given the complex evolutionary relationship between the dominant and non-dominant hands, this study focuses on identifying neuromotor differences associated with manual lateralization, through a comparative analysis of left-handed, right-handed, and ambidextrous individuals. To avoid biasing the data, we employ tasks that are not typically performed with both hands interchangeably, specifically, writing and drawing. According to our preliminary questionnaire, all participants reported having a preferred hand for writing, as this activity demands a high level of fine motor control, making it inefficient to perform with the non-dominant hand.

To investigate this, we designed an experiment in which participants perform both writing and free drawing tasks using each hand in a randomized order. The writing task allows for the analysis of fine motor execution in the active hand, while also observing the impedance control role of the contralateral hand, which stabilizes the paper during the activity. In contrast, the free drawing task involves more degrees of freedom and does not require as much fine motor precision, generating motor patterns that may also relate to creative expression.

The experiment involved both motion capture and EEG measurements. Participants provided informed consent by signing the Free and Informed Consent Form (Appendix 1). To ensure cognitive health, all subjects were screened using the Mini-Mental State Examination (MMSE) (Cockrell & Folstein, 2002) (Appendix 2). Manual lateralization was assessed using the Edinburgh Handedness Inventory (EHI) (Oldfield, 1971) (Appendix 3), which allowed us to classify participants as right-handed, left-handed, or ambidextrous. The experimental protocol was approved by the ethical committee of the Faculty of Federal University of Bahia (Certificate of Presentation for Ethical Appreciation: 68289021.5.0000.5531) in accordance with the Declaration of Helsinki.

The complex nature of neuromotor lateralization behavior involves a multitude of interacting variables, many of which cannot be isolated or modeled simultaneously. Evolutionary relationships are inherently non-linear, shaped by a dynamic interplay of biological, phenotypic, and sociocultural influences (Corballis, 2009; McManus, 2002). This complexity

limits the effectiveness of simplistic statistical approaches that seek to correlate isolated variables, such as comparing hand speed between dominant and non-dominant sides—without considering the broader system in which such behaviors emerge.

To meaningfully characterize neuromotor behavior, it is essential to analyze it holistically, using variables that dynamically represent movement profiles. This requires adopting tools from complexity science, which emerged as a non-reductionist paradigm aimed at identifying general patterns and systemic properties, rather than isolating discrete components (Mitchell, 2009; Nicolis & Prigogine, 1989).

For instance, rather than measuring only speed, an isolated outcome of motor execution, it is more informative to derive indices that relate movement dynamics to principles of motor optimization, such as energy efficiency, stability, and adaptability (Stergiou & Decker, 2011). Complexity-based methods, including fractal analysis, entropy measures, and recurrence quantification, allow us to detect emergent patterns in motor control that reflect the integration of sensory, cognitive, and biomechanical processes (Goldberger et al., 2002; Kelso, 1995).

This approach aligns with the theoretical framework proposed by Ilya Prigogine and others in the field of complex systems, where behavior is not simply the sum of its parts, but an emergent property of interacting components across scales and contexts.

Emergent behavior has the potential to condense and reveal previously hidden information, offering additional detail and insight into general motor and neural patterns. This is particularly important in the study of complex neurobehavioral systems, where non-linear interactions and temporal fluctuations play a critical role (Kelso, 1995; Freeman, 2000). For this reason, the present work combines two complementary studies: the first analyzes general biomechanical and EEG data across different hands and handedness profiles; the second focuses on the emergence of temporal dynamics by applying permutation entropy (PE) to motor and EEG time series. PE enables the quantification of complexity and temporal stability within these signals, providing a novel perspective on motor behavior and functional lateralization (Bandt & Pompe, 2002; Zanin et al., 2012). This combined approach allows for a more comprehensive

understanding of neuromotor strategies during fine motor tasks, by highlighting both static characteristics and dynamic, time-dependent features of behavior.

2. OBJECTIVE

The objective of this research is to characterize patterns of hand dominance by comparing the neural and biomechanical complexity of neuromotor behavior. Specifically, this study aims to analyze left-handed individuals as exceptions within the broader context of *Homo sapiens*' preference for right-hand dominance. By examining both neural activity and motor performance through complex systems approaches, we seek to identify whether left-handedness represents a distinct neuromotor profile rather than a simple inversion of right-handed behavior.

3. RESEARCH QUESTIONS

1. Are left-handed / ambidextrous individuals more or less optimized in neuromotor measurements compared to right-handed individuals?

This question investigates whether left-handedness is associated with different levels or types of motor efficiency, considering biomechanical and neural complexity.

2. What are the underlying factors that lead humans to develop a preferred hand?

This question explores the biological and social aspects behind manual lateralization in *Homo sapiens*.

3. Do social and cultural factors influence hand preference and hand-dependent motor behavior?

This question addresses the role of environmental, educational, and cultural experiences in shaping patterns of handedness, particularly in societies where left-handedness is stigmatized or discouraged.

4. THEORETICAL REFERENCE

The human brain exhibits hemispheric specialization, with the left hemisphere predominantly supporting language and analytical functions, and the right hemisphere more engaged in visuospatial and integrative processes (Dimond & Beaumont, 1974). This asymmetry underlies patterns of hand dominance: right-handers typically show left-hemispheric dominance for both language and motor functions, while left-handers often present more variable patterns of lateralization, ranging from right-hemisphere dominance to bilateral organization (McManus, 2009; Gazzaniga & LeDoux, 2013). Such variability suggests increased interhemispheric communication and neural flexibility among left-handers, potentially supporting greater adaptability in motor and cognitive tasks.

Early neuroimaging and hormonal studies proposed prenatal factors, such as testosterone exposure, as contributors to hemispheric asymmetry (Geschwind & Galaburda, 1987), while genetic studies have identified heritable components influencing handedness and brain lateralization (McManus et al., 2009). Behavioral research complements these findings: right-handers typically exhibit superior motor precision with their dominant hand, linked to more lateralized cortical activation, whereas left-handers often demonstrate greater ambidexterity and motor adaptability (Ghosh et al., 2008).

Electroencephalographic (EEG) studies reveal that right-handers show stronger interhemispheric coherence and greater contralateral motor cortex activation during dominant hand tasks. In contrast, left-handers tend to display more symmetric or less lateralized activation, particularly in the alpha and beta frequency bands, which may reflect distributed motor planning networks (Ghosh et al., 2008; Kottlow et al., 2010). These neural dynamics suggest that left-handers may possess enhanced capacity for bilateral motor coordination and hand-switching flexibility.

Functional neuroimaging (e.g., fMRI) has further highlighted differential activation patterns between groups during tasks requiring fine motor control and visuospatial integration, such as writing and drawing. For instance, artists—who often engage both hands—demonstrate reduced upper alpha power in parietal regions, implying heightened visuo-motor engagement

(Kottlow et al., 2011). Such findings underscore how lateralization, skill acquisition, and hand dominance interact to shape motor-cognitive function.

Despite decades of research, the field continues to rely on simplified motor metrics such as reaction time and grip strength, which fail to capture the complexity of motor behavior (Tiffin & Asher, 1948). Standardized scales like the Fugl-Meyer Assessment (FMA) also emphasize isolated movements rather than integrative motor tasks (Gladstone et al., 2002). To address this limitation, Miranda et al. (2018) proposed a complex systems approach to handwriting analysis, identifying nonlinear motor patterns, though this framework lacks analysis of handedness-specific variations. Our study builds upon this by investigating whether such nonlinear signatures differ between dominant and non-dominant hands, particularly in left-handed individuals.

In sum, handedness is not merely a matter of motor preference—it reflects distinct neural architectures and behavioral strategies that influence motor control, cognitive flexibility, and rehabilitation outcomes. Understanding these differences provides a valuable window into the brain's plasticity, with implications for both fundamental neuroscience and applied clinical practices.

5. PAPER 1

Handedness and Brain Lateralization: a nonlinear motor approach combined with EEG

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ABSTRACT

This study explores handedness through a multidisciplinary approach, integrating biomechanical analysis and electroencephalography (EEG) to uncover differences in motor strategies and brain lateralization among right-handed, left-handed, and ambidextrous individuals. Seventy participants were assessed using motion capture and EEG during writing and drawing tasks performed with both dominant and non-dominant hands. Biomechanical data were analyzed using the Movement Element Decomposition (MED) method, while EEG data focused on event-related synchronization/desynchronization (ERD/S) patterns. Results highlight that right-handers demonstrate stronger lateralization for fine motor tasks, with optimized neural and biomechanical adaptations favoring the right hand. In contrast, left-handers exhibit specialization for impedance control with their right hand, suggesting distinct motor planning strategies. EEG findings corroborate these behaviors, showing that right-handers require less cognitive effort when using their dominant hand for writing, whereas left-handers show heightened parietal activity associated with sensorimotor integration during similar tasks. The study reveals an asymmetry in motor skill acquisition, possibly related to left-handed adaptations to right-hand-dominated environments. These insights contribute to

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understanding handedness's role in motor control and brain organization, with implications for neurorehabilitation.

Keywords: Handedness, Brain Lateralization, Motor Control, Impedance Control, Movement Element Decomposition.

5.1. Introduction

Motor lateralization manifests in various ways; some individuals exhibit a preference for one eye while favoring the opposite foot, highlighting its complexity (Coren, Porac, & Duncan, 1979; Brackenridge, 1981). Although numerous studies have explored lateralization across different tasks, hand dominance referred to as handedness is the most studied form. Estimates suggest that approximately 90% of the human population prefers the right hand for manual tasks (Brackenridge, 1981; Teixeira, 2006). However, Sainburg (2014) argues that motor control is inherently bimanual, with the dominant hand specializing in fine motor tasks (e.g., writing, drawing, or tool manipulation) while the non-dominant hand primarily contributes to impedance control, stabilizing movements. For example, when cutting bread, the dominant hand executes the cutting motion, whereas the non-dominant hand stabilizes the loaf.

Handedness presents an important problem in understanding brain lateralization, motor control, and neural adaptations, offering insights into the interplay between cognition and movement. Historically, handedness has been a marker of societal and cultural biases. Left-handed individuals, for example, were often subjected to forced hand-switching, leading to adverse consequences such as speech impediments and stuttering (Harris, 2012; Wolman, 2005; Guenther, 2018). These practices highlight the longstanding tension between societal norms and natural biological variation, underscoring the need to better understand the foundations and implications of handedness (Hardie et al., 2016).

Handedness reflects not only a balance between biology and environment but also diverse motor strategies and neural adaptations, changing how we develop our fine motor skills (Parish et al., 2013; Nalçacı et al., 2001; Arndt, 2003; Yetkin, 2012; Mentese, 2024). Right-handed individuals typically demonstrate strong left-hemisphere dominance, facilitating precise motor control for tasks like writing (Yadav & Sainburg, 2014A; Yadav & Sainburg, 2014B; Judge & Stirling, 2003). In contrast, left-handers exhibit more variable lateralization patterns in the brain and in the hand motion, relying on both hemispheres or showing right-hemisphere shifts for

motor and cognitive tasks. Interestingly, some studies suggest left-handers may surpass right-handers' accuracy in fine motor skills (Mentese & Kutlu, 2024; Judge & Stirling, 2003), reflecting a spectrum of motor and neural strategies shaped by individual differences (McManus, 1992; Corballis, 2009).

However, key gaps remain. While previous studies provide valuable insights into handedness and its impact on brain organization and motor control, traditional measures such as reaction time and grip strength fail to capture the nuanced biomechanical and neural mechanisms underlying these differences (Aune et al., 2021). For instance, emerging evidence suggests that left-handers employ distinct motor strategies, such as specialized right-hand impedance control during stabilization tasks (Sainburg, 2014). Additionally, EEG studies reveal handedness-specific patterns of cortical activation, including greater bilateral activity in left-handers compared to the pronounced lateralization seen in right-handers (McManus, 2009; Serrien & Sovijärvi-Spapé, 2016; Gazzaniga & LeDoux, 2013; Kottlow et al., 2011). Despite these advances, much remains to be explored about how these adaptations influence motor and cognitive functions in daily life.

Traditional metrics in biomechanics fail to bring interpretations related to cognitive activation patterns. To fill this gap, this study addresses advanced tools brought from Movement Element Decomposition (MED). These tools contain features related to motor control and skill acquisition (Miranda et al., 2018; Fonseca et al., 2019). We also compare with EEG analysis to investigate motor strategies and brain lateralization across handedness groups. By integrating biomechanical and neurophysiological data, we seek to uncover the unique adaptations associated with handedness. These findings hold potential applications for neurorehabilitation, motor skill training, and ergonomic design, offering a deeper understanding of the relationship between handedness and human performance.

5.2. Methods

This work contains methods for collecting and analyzing biomechanical and EEG data, with more details on the processing steps in supplementary material 1- A.

5.2.1. Experimental setup

Seventy participants were recruited, including right-handed, left-handed, and ambidextrous individuals, classified based on the Edinburgh Handedness Inventory (EHI) (Oldfield, 1971).

Cognitive function was assessed using the Mini-Mental State Examination to ensure no impairments. To participate in the EEG collection, subjects with no neurological disorder must have a grade greater than 25 points in the Mini-Mental State Examination (MMSE) (Cockrell & Folstein, 2002). The experiment measured brain activity using an EEG cap and the movement of the hands and the tip of the pen using an OptiTrack Motion Capture device. The experimental protocol was approved by the ethical committee of the Farmacy Faculty of Federal University of Bahia (Certificate of Presentation for Ethical Appreciation: 68289021.5.0000.5531) in accordance with the Declaration of Helsinki.

The protocol is divided into three parts: EEG basal activity, writing, and free drawing. The tasks will be performed once with each hand, and the order in which the hand is used will be randomized. The volunteer will be invited to sit in a chair with a table in front containing papers and a pen to carry out the following tasks (Figure 5.1):

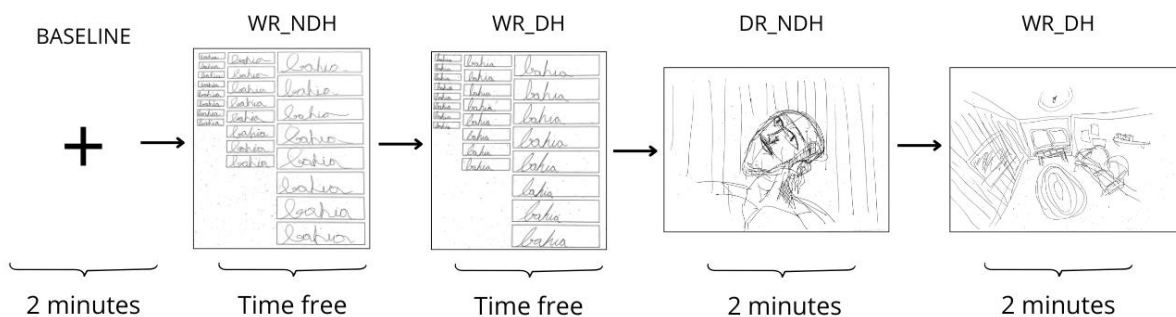


Figure 5.1: Example of experiment sequence: WR_NDH: Writing with non-dominant hand; WR_DH: Writing with dominant hand; DR_NDH: Drawing with non-dominant hand; DR_DH: Drawing with dominant hand.

EEG Basal Activity – The participant should remain seated, with their forearms resting on the table, eyes closed, and facing the table for 120 seconds to capture EEG baseline data for reference.

Writing (WT) – The participant will be asked to write the word “bahia” in cursive on an A4 sheet of paper, filling in each of the 24 printed boxes on the paper, in three different scales. The word "bahia" was chosen for being familiar to the participants and something they had written

multiple times. There is no specified time for this task, allowing the participant to write as naturally as possible. The task is performed once with each hand.

Drawing (DR) – The participant should create a free drawing during the task, which may be realistic or abstract, according to their preference. This drawing will be made on an A4 sheet of paper over a period of 120 seconds. The task is performed once with each hand.

Both the duration of the free drawing and the number of times the writing task is performed were designed to ensure that at least 120 seconds of EEG data is collected for each recording. These values were established based on pilot tests.

Biomechanical collection			
	Left-handed	Ambidextrous	Right-handed
Female	27.5 ± 2.8 (12 subjects)	-	23.3 ± 3.7 (10 subjects)
Male	22.2 ± 1.3 (11 subjects)	29.1 ± 2.9 (9 subjects)	24.6 ± 1.3 (19 subjects)
EEG collection			
Female	27.9 ± 3.0 (11 subjects)	-	27.4 ± 7.2 (5 subjects)
Male	22.1 ± 1.4 (10 subjects)	29.1 ± 2.9 (9 subjects)	24.1 ± 1.2 (21 subjects)

Table 5.1: Mean age and standart deviation by handedness group and sex in collections.

All participants were healthy volunteers from the university campus, including undergraduate and graduate students, technical workers, and professors. We invited participants that have a habit of writing and rarely draw. No monetary compensation was provided. After excluding data with low quality or non-approval in MMSE. In the biomechanical collection we had 63 subjects: 30 right-handers, 10 ambidextrous and 23 left-handers; In the EEG collection we had 56 subjects: 26 right-handers, 9 ambidextrous and 21 left-handers. Total mean age: 25.78.3 years old. (See subject's classification data on Table 5.1)

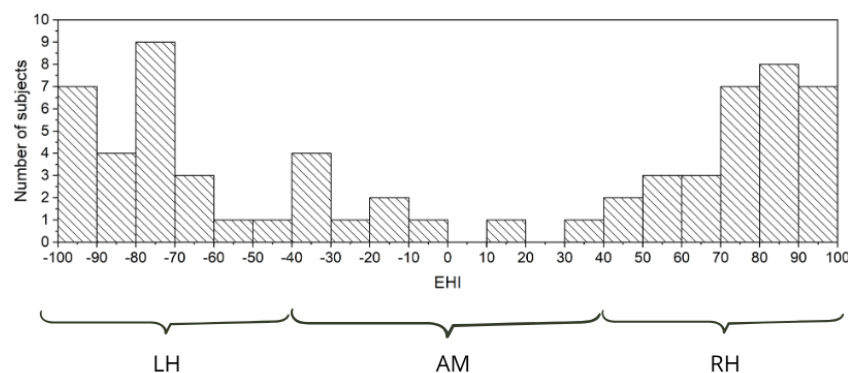


Figure 5.2: histogram of the EHI laterality coefficient among the subjects invited.

The EHI test provides a Laterality Coefficient, a score ranging from -100 to 100, where individuals are classified as left-handed (-100 to -40), ambidextrous (-40 to 40), or right-handed (40 to 100). Our dataset exhibited a wide range of laterality coefficients (see Figure 5.2). No participants self-identified as ambidextrous. Interestingly, one participant who self-identified as right-handed and nine who self-identified as left-handed fell within the ambidextrous range based on their EHI scores. For analyses requiring dominant and non-dominant hand assignments, we used each participant's self-reported preferred hand for the specific task.

5.2.2. Biomechanical approach

The analysis method developed by Miranda et al. (2018), hereby termed Movement Element Decomposition (MED in Figure 5.3), incorporates the minimum jerk principle proposed by Flash & Hogan (1975) and extended by Hoff (1994), where the most optimal reaching movement should follow the equation:

$$v(t) = D[30 \frac{t^4}{tf^5} - 60 \frac{t^3}{tf^4} + 30 \frac{t^2}{tf^3}] \quad (5.1)$$

Where tf is the duration of the movement, and D is the displacement. Miranda's approach focuses on characterizing the underlying principles of complex three-dimensional upper-limb movements by decomposing them into simpler one-dimensional elements with predictable velocity profiles. Each element range is defined between consecutive zero velocity crossings, decomposed within a Cartesian coordinate system.

The number of movement elements is a key feature in motor control, as it relates to the number of zero crossings in velocity. Individuals proficient in certain movements require fewer elements to complete a task (Fonseca et al., 2019). A lower number of movement elements indicates greater stability and smoother execution. Given the flexible timing in writing tasks, we also consider the frequency of elements, measured as the number of elements per second.

Additional features associated with the relation between the elements provide insights into the motor strategy, such as the relation between mean velocity ($\bar{v}$) and displacement D for each element (Miranda et al., 2018):

$$\bar{v} \propto D^\alpha \quad (5.2)$$

Miranda et al. (2018) found that the exponent relates to movement optimization and motor planning, and that this exponent has an average value of $\alpha = \frac{2}{3}$ in upper limb movements. Within the framework of Hoff's proposed model, this indicates that selecting velocity as a function of the reaching movement sizes achieves a balance in the optimization process, equally minimizing the time and smoothness of the movements. An additional feature that can be extracted from MED involves comparing the shapes of movement elements with the theoretical curve obtained using equation (1) to quantify motor elements quality. This is done using the W index, defined by Fonseca et al. (2019) as :

$$W = std(v - HC) / \bar{v} \quad (5.3)$$

Where v is the measured velocity profile, HC is the theoretical Hoff (1994) curve (1), and $\bar{v}$ is the mean velocity of the measured profile.

The current work will examine these features to characterize handedness and evaluate motor planning and motor skill acquisition. A higher W value means more error compared to the theoretical best-balanced function. Oubre et al. (2021) found different elements based on how they differ from the standard model Eq. 5.1, comparing elements of subjects with ataxia and healthy subjects. They found that subjects with ataxia use more types of elements in their movement, relating element variation to a motor disorder.

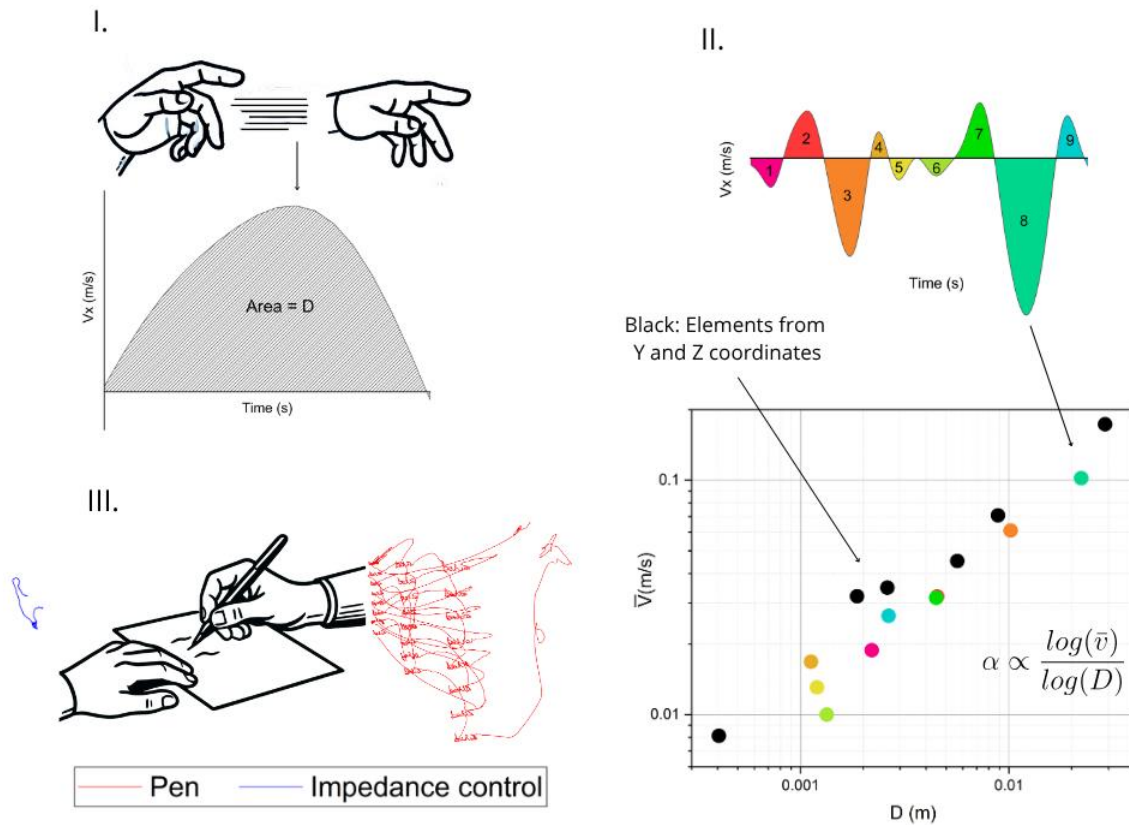


Figure 5.3: I- Simple movement element decomposition in X direction. II- Movement Element Decomposition, where each element is defined when the velocity crosses zero. III- An example of the movements collected, with the right hand performing the task and the left hand performing the impedance control movement.

The biomechanical assessment included the following indices:

- **α :** Represents the motor planning strategy, calculated as the slope of the best linear fit between $\log(\bar{v})$ and $\log(D)$ for elements in the x, y, and z coordinates (Figure 5.3-II, Eq. 5.2). Only data with a strong correlation ($r \geq 0.7$) are considered.
- **W :** Indicates the proximity of the executed velocity profile to Hoff's theoretical model Eq. 5.3.
- **N_e :** The number of movement elements used to perform the task, related to how many oscillations and direction changes the movement needed.
- **N_{eps} (Ne/s):** The number of elements per unit of time.
- **Trajectory (m):** Scalar sum of all displacements performed during a task
- **Mean velocity (m/s):** The average speed over the entire task.

To analyze both task execution movements with both hands and the impedance control movements during the writing process (see Figure 5.3-III), we examined all biomechanical measures shown. Given the small-scale nature of impedance control movements, we focused only on scale size-independent variables: W, Ne, and Neps.

5.2.3. EEG collection and processing methodology

For collecting EEG data, we used a 64-electrode cap Compumedics Neuroscan Neuvo. Electrode impedance was calibrated to remain below 60 k Ω . For analysis, specific electrodes corresponding to targeted brain regions were selected. This study utilized a quantitative EEG (qEEG) approach to investigate the relationship between handedness and brain lateralization. EEG data were recorded with a multi-channel system, adhering to the International 10-10 placement system, at a sampling frequency of 1000 Hz.

Participants performed motor tasks with both their dominant and non-dominant hands while EEG signals were captured. Signal preprocessing included digitization and artifact removal, such as eye blinks and muscle activity, via Independent Component Analysis (ICA) (Jung et al., 2000). Power spectral density (PSD) analysis was subsequently employed to quantify beta-frequency amplitude across cortical regions, providing detailed insights into task-related cortical activity.

Electrodes were deemed as major regions as described, as follows:

- FR (Right frontal) = {'FP2', 'AF4', 'F10', 'F8', 'F6', 'F4'};
- FL (Left frontal) = {'FP1', 'AF3', 'F9', 'F7', 'F5', 'F3'};
- CR (Right central) = {'FC6', 'FC4', 'FC2', 'F2', 'C6', 'C4', 'C2'};
- CL (Left central) = {'FC5', 'FC3', 'FC1', 'F1', 'C5', 'C3', 'C1'};
- TR (Right temporal) = {'TP8', 'T8'};
- TL (Left temporal) = {'TP7', 'T7'};
- PR (Right parietal) = {'CP6', 'CP4', 'CP2', 'P10', 'P8', 'P6', 'P4', 'P2'};
- PL (Left parietal) = {'CP5', 'CP3', 'CP1', 'P9', 'P7', 'P5', 'P3', 'P1'};
- OR (Right occipital) = {'PO4', 'O2', 'CB2'};
- OL (Left occipital) = {'PO3', 'O1', 'CB1'};

The qEEG data was then statistically analyzed, considering the brain regions' mean power across electrodes to compare the hemispheric differences in brain activity between tasks performed with the dominant and non-dominant hands. This approach enabled us to explore the neural mechanisms underlying handedness and how they relate to brain lateralization. By

integrating qEEG into our methodology, we obtained a detailed and objective analysis of brain function during motor tasks, providing a comprehensive understanding of the neural processes involved in handedness and lateralization.

To compute EEG signals are typically band-pass filtered to isolate frequencies of beta (13–30 Hz) band, previously shown as an important frequency range for fine motor tasks execution (Serrien & Sovijärvi-Spapé, 2016). The power is then calculated for each time window relative to a baseline period before movement initiation. To assess brain cognitive activation, we compute event-related desynchronization/synchronization (ERD/S). Specifically, ERD/S is defined as the percentage change in power relative to a baseline (see Eq. 5.4). A negative ERD/S value indicates a reduction in power, reflecting increased cognitive load, while a positive value indicates an increase in power, which corresponds to decreased cognitive load (Lajtos, Barradas-Chacón & Wriessnegger, 2023). This calculation follows the equation:

$$ERD/S = \frac{A - B}{B} \quad (5.4)$$

Where A is the sample power during activation, and B is the baseline.

To assess differences in cerebral activation patterns across tasks and handedness groups, we employed a matrix-based visualization schema, as depicted in Figure 5.5. This schema represents significant differences between conditions (row minus column comparisons, Eq. 5.5) through color-coded cells: green indicates a significant increase in cognitive load, and orange indicates a significant decrease. Unpainted regions indicate no statistically significant differences between the compared conditions.

$$\Delta ERD/S(I, J) = ERD/S(I) - ERD/S(J) \quad (5.5)$$

For example, in Figure 5.5, a comparison between writing with the dominant hand (WR_DH) and drawing with the non-dominant hand (DR_NDH) revealed distinct brain activation patterns. Specifically, a significant increase in cognitive activation (decrease in $\Delta ERD/S$) in the left parietal lobe (represented by green) and a significant decrease in cognitive activation (increase in $\Delta ERD/S$) in the left temporal and right parietal lobe (represented by orange). These findings highlight task- and handedness-dependent variations in neural engagement, providing insights into brain regions' lateralization and functional specialization during motor and cognitive tasks.

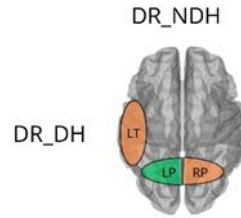


Figure 5.5: An example of a matrix cell of statistical significance of ERD/S results. It compares drawing with the dominant hand (row DR_DH) and the non-dominant hand (column DR_NDH).

5.3. Results

Results are based on statistical analysis divided in Biomechanical: task execution and impedance control, and neural: EEG results.

5.3.1. Task execution movements results

Hand dominance plays a critical role in task performance, particularly in activities that demand fine motor control, such as writing and drawing. To investigate this, we conducted a 2x2x3 ANOVA (task, hand, group) and found distinct patterns in motor strategies and neural adaptations based on task type and handedness. Our findings reveal that some measures are more sensitive to these differences than others. Specifically, significant differences emerged in α (F: 92.059, $p=0.000$) and Ne (F: 21.380, $p=0.000$) when comparing tasks, while Neps (F: 43.762, $p=0.000$) and *Mean Velocity* (F: 19.593, $p=0.000$) were sensitive to the hand used. However, no significant differences were observed when comparing groups overall, suggesting that the observed variations are task- and hand-specific rather than group-wide.

Task execution - Post Hoc - comparisons between dominant and non-dominant hands						
Measure	Group	Task	Mean(DH) $\pm$ SE	Mean(NDH) $\pm$ SE	Mean Difference (DH-NDH)	P value
α	LH	Writing	0.711 $\pm$ 0.014	0.706 $\pm$ 0.013	0.005	0.747
		Drawing	0.638 $\pm$ 0.020	0.624 $\pm$ 0.012	0.014	0.519
	AM	Writing	0.670 $\pm$ 0.022	0.705 $\pm$ 0.020	-0.034	0.168
		Drawing	0.612 $\pm$ 0.030	0.618 $\pm$ 0.019	-0.006	0.857
	RH	Writing	0.687 $\pm$ 0.012	0.729 $\pm$ 0.012	-0.042*	0.005
		Drawing	0.656 $\pm$ 0.017	0.622 $\pm$ 0.011	0.034	0.078
Neps (Ne/s)	LH	Writing	5.199 $\pm$ 0.305	3.460 $\pm$ 0.274	1.74*	0
		Drawing	5.243 $\pm$ 0.397	5.042 $\pm$ 0.345	0.2	0.612

W	AM	Writing	5.925±0.463	3.871±0.416	2.05*	0
		Drawing	4.295±0.602	4.156±0.524	0.138	0.817
	RH	Writing	5.878±0.267	3.864±0.240	2.02*	0
		Drawing	4.995±0.347	4.430±0.302	0.565	0.105
	LH	Writing	0.437±0.006	0.453±0.004	-.016*	0.008
		Drawing	0.436±0.007	0.438±0.005	-0.002	0.816
	AM	Writing	0.438±0.009	0.446±0.007	-0.008	0.341
		Drawing	0.438±0.010	0.437±0.008	0.001	0.962
	RH	Writing	0.435±0.005	0.444±0.004	-0.008	0.1
		Drawing	0.447±0.006	0.446±0.004	0.001	0.831
	LH	Writing	714.217±31.808	862.870±30.205	-148.65*	0
		Drawing	697.130±53.812	697.391±50.033	-0.261	0.996
	AM	Writing	750.700±48.240	760.200±45.808	-9.5	0.827
		Drawing	591.100±81.610	561.600±75.879	29.5	0.736
	RH	Writing	737.833±27.851	911.733±26.447	-173.90*	0
		Drawing	669.800±47.118	580.200±43.809	89.6	0.08
Trajectory (m)	LH	Writing	11.979±1.314	12.616±1.490	-0.637	0.694
		Drawing	11.227±1.285	9.923±0.799	1.304	0.286
	AM	Writing	8.539±1.993	10.219±2.259	-1.68	0.493
		Drawing	10.765±1.949	7.719±1.212	3.046	0.102
	RH	Writing	10.460±1.151	10.696±1.304	-0.236	0.867
		Drawing	10.799±1.125	8.055±0.700	2.74*	0.012
	LH	Writing	0.087±0.012	0.047±0.004	.040*	0.001
		Drawing	0.084±0.009	0.072±0.006	0.011	0.159
Mean Velocity (m/s)	AM	Writing	0.067±0.018	0.051±0.006	0.017	0.328
		Drawing	0.074±0.013	0.057±0.009	0.017	0.168
	RH	Writing	0.087±0.010	0.043±0.004	.043*	0
		Drawing	0.080±0.008	0.062±0.005	.019*	0.009

*. The mean difference is significant at the .05 level.

Adjustment for multiple comparisons: Bonferroni.

Table 5.2: Biomechanical measurements in task execution movements, comparison between hands for left-handed (LH), and ambidextrous (AM) and right-handed (RH).

Post hoc analyses (Table 5.2) offer deeper insights into these findings. Among right-handers, trajectory differences between hands were observed only in the drawing task, whereas mean velocity differed between hands in both tasks. In contrast, left-handers showed no significant differences in trajectory but exhibited significant differences in mean velocity exclusively during the writing task. Notably, right-handers demonstrated greater sensitivity by minimizing movement when drawing with their non-dominant hand.

Figure 5.6 shows the relation between the biomechanical indices (Ne and Neps) and the laterality coefficient. Our results suggest that handedness influences motor strategies asymmetrically. For example, in the writing task, anti-symmetrical behavior was observed in the Ne difference between hands (Ne(right) - Ne(left)) and the laterality coefficient from the

EHI. Right-handers and left-handers showed opposing patterns, whereas ambidextrous individuals exhibited no clear differences. This makes Ne a promising index for quantifying hand dominance. Interestingly, the difference in elements per second ($Neps$, $Neps(right) - Neps(left)$) showed the opposite symmetry and was significant across all groups. This suggests that while the dominant hand executes more movements per second, the non-dominant hand contributes more overall elements.

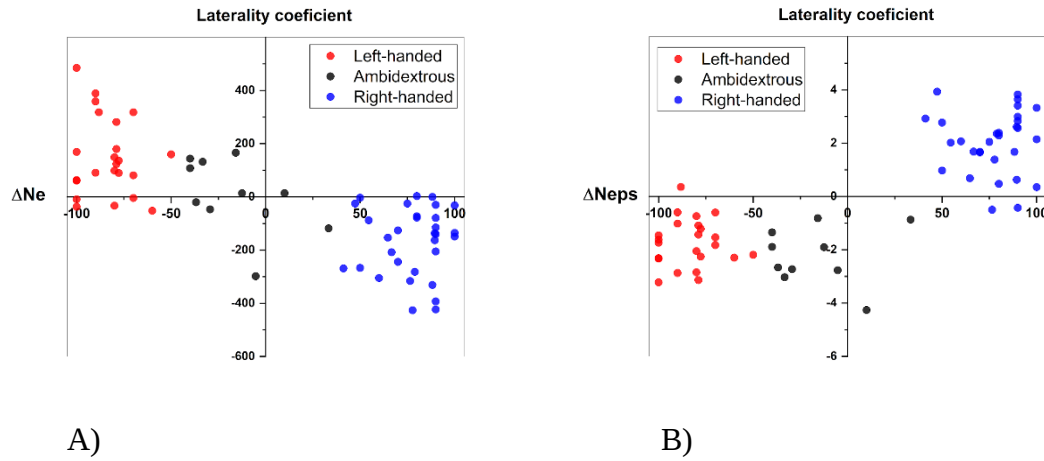
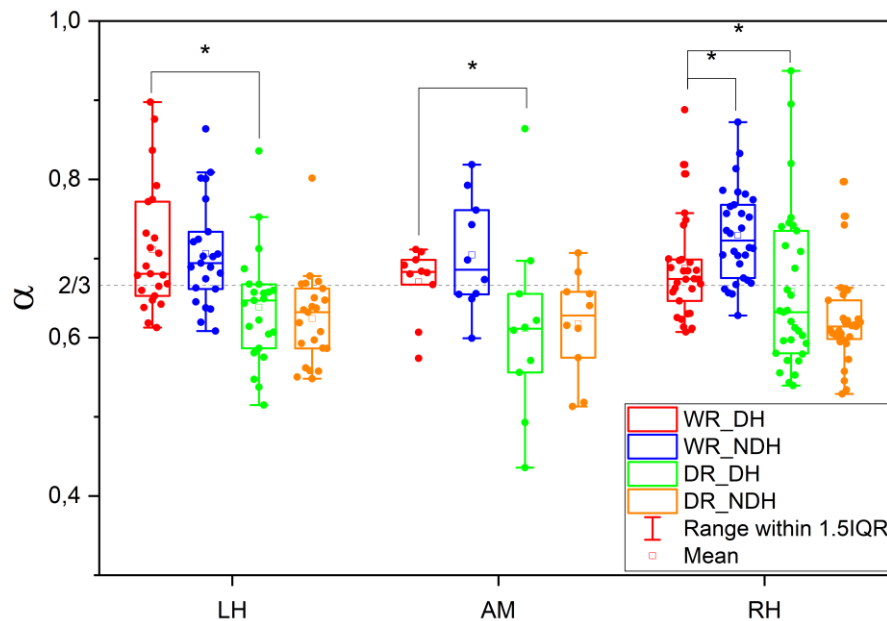


Figure 5.6: A: ΔNe in function of Laterality coefficient in the writing task; B: $\Delta Neps$ in function of Laterality coefficient in the writing task.

Another critical finding relates to the W index, which is associated with skill acquisition processes (Fonseca et al., 2019). In left-handers, the W index showed significant differences between hands during the writing task and higher W in the non-dominant hand. Therefore, the motor profile is further away from the reference function Eq. 5.1. This suggests that their non-dominant hand exhibits worse motor capabilities. In contrast, right-handers demonstrated no significant difference in the W index between hands, indicating a more hand-independent motor strategy. These results suggest that left-handed individuals develop distinct motor learning patterns in their dominant hand, whereas right-handers rely on a more uniform approach across both hands. The drawing task, in contrast, showed no significant differences in W or other metrics between hands. This suggests that creative drawing relies on less specialized motor strategies compared to writing, which requires a greater degree of precision and coordination. Motor strategies, as represented by the exponent α , play a crucial role in balancing energy and time (Miranda et al., 2018). Comparisons across tasks reveal that α values tend to be higher in

writing than in drawing across all groups. In writing, α approaches $2/3$, suggesting a stronger emphasis on motor efficiency, whereas in free drawing, precision is less important. Interestingly, significant differences between hands were observed only in the right-handed group, indicating a stronger hand dependency for this fine motor task (see Figure 5.7).



*($p < 0.05$)

Figure 5.7: Comparison of α values in the tasks, considering execution movements (WR_DH, WR_NDH, DR_DH, DR_NDH) across groups.

5.3.2. Impedance control movement results

We conducted another $2 \times 2 \times 3$ ANOVA (task, hand, group) for impedance control movements analysis, focusing on differences between hands (Table 5.3). A more detailed analysis of movement dynamics highlighted the critical role of the non-dominant hand in impedance control. During writing tasks, both hands contributed distinct movement components, with the non-dominant hand primarily providing stabilizing support. Notably, left-handed individuals exhibit significantly fewer impedance control elements in their dominant hand compared to right-handed individuals. Specifically, the non-dominant hand of left-handers demonstrated,

on average, 170.5 fewer elements (Ne) in impedance control movements ($p = 0.038$), underscoring its specialized role in stabilization. No differences have been found in Neps.

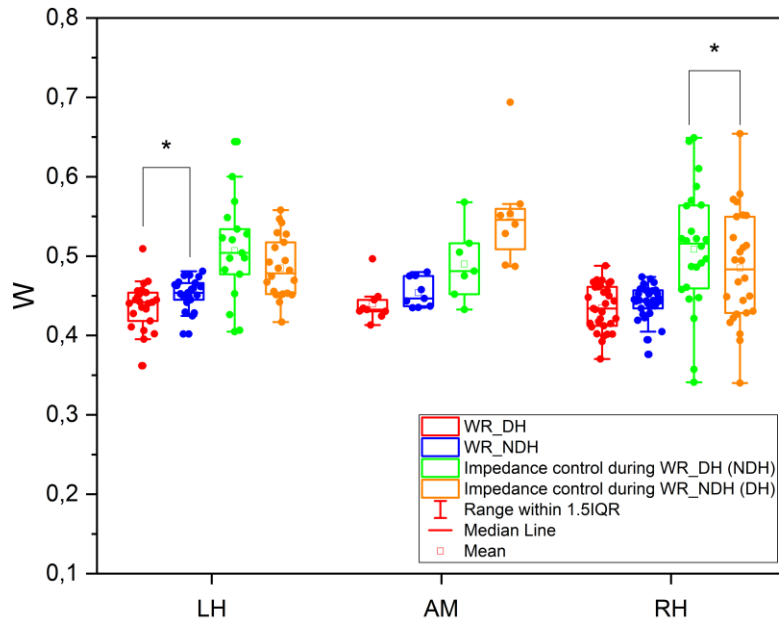
Impedance Control - Post Hoc - comparisons between dominant and non-dominant hands						
Measure	Group	Task	Mean(NDH during DH execution) $\pm$ SE	Mean(DH during NDH execution) $\pm$ SE	Mean Difference (NDH-DH)	P value
Neps (Ne/s)	LH	Writing	0.384 $\pm$ 0.098	0.803 $\pm$ 0.282	-.419	.166
		Drawing	0.902 $\pm$ 0.291	0.925 $\pm$ 0.282	-.023	.959
	AM	Writing	0.631 $\pm$ 0.139	0.428 $\pm$ 0.399	.203	.628
		Drawing	0.164 $\pm$ 0.412	0.272 $\pm$ 0.399	-.108	.864
	RH	Writing	0.242 $\pm$ 0.064	0.457 $\pm$ 0.185	-.215	.272
		Drawing	0.269 $\pm$ 0.191	0.293 $\pm$ 0.185	-.024	.933
W	LH	Writing	0.513 $\pm$ 0.026	0.477 $\pm$ 0.021	.035	.273
		Drawing	0.550 $\pm$ 0.023	0.498 $\pm$ 0.014	.052	.065
	AM	Writing	0.492 $\pm$ 0.037	0.530 $\pm$ 0.030	-.039	.393
		Drawing	0.522 $\pm$ 0.032	0.493 $\pm$ 0.020	.029	.445
	RH	Writing	0.540 $\pm$ 0.017	0.494 $\pm$ 0.014	.046*	.037
		Drawing	0.510 $\pm$ 0.015	0.496 $\pm$ 0.009	.014	.435
Ne	LH	Writing	40.500 $\pm$ 15.276	211.000 $\pm$ 78.532	-170.500*	.038
		Drawing	114.833 $\pm$ 39.335	121.500 $\pm$ 37.398	-6.667	.909
	AM	Writing	86.667 $\pm$ 21.604	92.333 $\pm$ 111.062	-5.667	.959
		Drawing	21.000 $\pm$ 55.628	34.333 $\pm$ 52.889	-13.333	.872
	RH	Writing	31.929 $\pm$ 10.001	121.143 $\pm$ 51.412	-89.214	.091
		Drawing	41.714 $\pm$ 25.751	40.071 $\pm$ 24.483	1.643	.966

*. The mean difference is significant at the .05 level.

Adjustment for multiple comparisons: Bonferroni.

Table 5.3: Biomechanical measurements in task impedance control movements, comparison between hands.

We observed a significantly higher W in the non-dominant hand's impedance control among right-handers ($p = 0.037$), indicating that they exhibit more skillful impedance control with their dominant hand. In contrast, task execution results point in the opposite direction: left-handers demonstrate worse performance with their dominant hand compared to the reference for optimized movement in Eq. 5.1 (see Figure 5.8). This asymmetrical behavior suggests that right-handers excel in fine motor tasks, whereas left-handers are more proficient in impedance control.



*($p < 0.05$)

Figure 5.8: Comparison of W values in writing tasks, considering execution movements (WR_DH, WR_NDH) and the corresponding impedance control exerted by the assisting hand (Impedance control during WR_DH, Impedance control during WR_NDH) across groups.

In summary, these findings underscore the complexity of motor strategies across handedness groups. The writing task emerged as a key activity for distinguishing motor adaptations, revealing both inter- and intra-hand differences. Right-handers showed greater specialization and balance in their dominant hand, while left-handers demonstrated robust motor learning and stabilizing adaptations. These results provide valuable insights into the biomechanical and neural mechanisms underlying handedness and highlight potential applications for neurorehabilitation, skill training, and movement sciences.

5.3.3. EEG results

We analyzed writing and drawing tasks using EEG data to explore cognitive load associated with hand dominance and task specialization. Writing and drawing with the dominant and non-dominant hand were the compared tasks to capture the nuanced neural behaviors linked to hand changes. This distinction allowed us to conduct a $4 \times 10 \times 3$ ANOVA (Task, Region, Group),

which revealed significant differences across brain regions ($F: 3.76683$, $P=0.0255$). This outcome aligns with the established understanding that distinct brain regions perform specialized functions. However, no direct differences were observed between tasks, or groups; these results became evident only in the Post Hoc analysis (Figure 5.9). The comparison data is in the supplementary material 1-B.

A detailed evaluation of the quantitative EEG data highlighted key distinctions between groups. Ambidextrous individuals exhibited high variability, with no significant differences detected, suggesting a lack of clear neural specialization for either hand.

Right-handers displayed significant decrease in cognitive load in the left central lobe comparing WR_DH and all the others tasks (Figure 5.9-B-i,ii, and iii), representing the motor area related to the right arm movement (Lajtos, Barradas-Chacón & Wriessnegger, 2023). Left-handers, in contrast showed significant increased in the right parietal lobe in the WR_DH and WR_NDH comparison (Figure 5.9-A-i), emphasizing the role of the non-dominant hand in stabilizing or impedance control. We have also a significant decrease of cognitive load in left temporal lobe comparing WR_DH and tasks played with the non dominant hand (Figure 5.9-B-i and iii), this area is often related to memory processes (Squire, 2004).

Drawing tasks exhibited a different neural profile. Right-handers showed no significant differences in ERD/S between dominant and non-dominant hands in the central lobes, but in showed a left parietal increase and right parietal decrease (Figure 5.9-B-vi). Left-handers, however, exhibited differences in the right central lobe, with higher cognitive load when drawing with the dominant hand (Figure 5.9-A-vi).

Comparing WR_DH and DR_DH for right-handed group we found significant decrease in left central and a increase in left parietal lobe (Figure 5.9-B-ii)., It means that the cost of writing is lower in left central lobe and higher in parietal lobe. Regions related to right arm stimulation activity (Brunoni et al., 2012, Silva et al., 2021) and motor stabilization (Ehrsson et al., 2000; Hülzdünker et al., 2015; Milner et al., 2006) respectively. No significant difference was found in the left-handed group (Figure 5.9-A-ii).

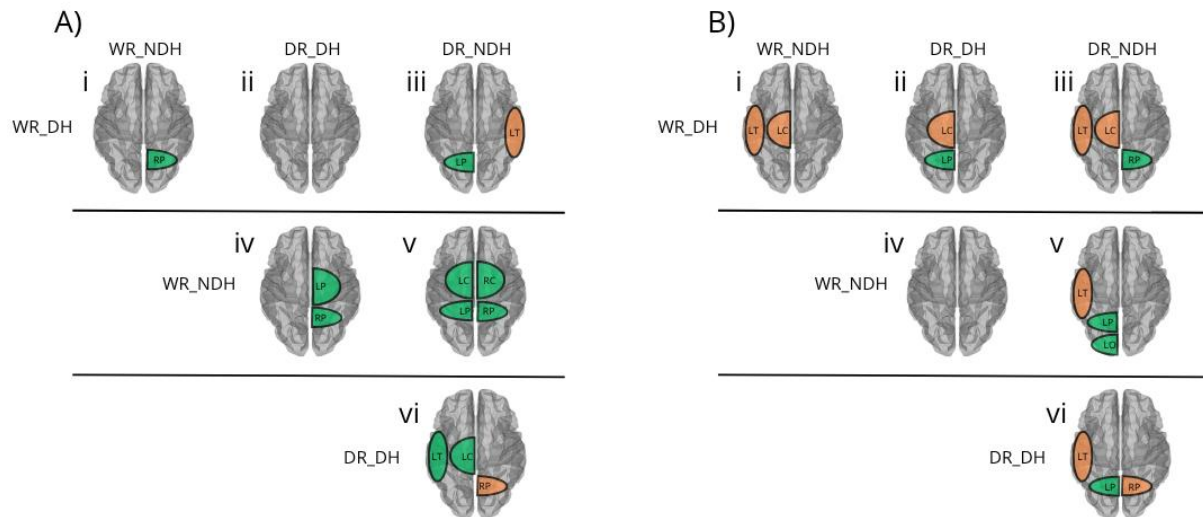


Figure 5.9: ERD/S Post Hoc matrices comparing tasks (line subtracting column): writing with dominant hand (WR_DH), writing with non-dominant hand (WR_NDH), drawing with dominant hand (DR_DH), drawing with non-dominant hand (DR_NDH). Representing a significant increase of cognitive activation as a green area and a decrease with an orange area: A- Left-handers results, B- Right-handers results. No significant difference was found in the Ambidextrous group.

5.4. Discussion

Due the number of biomechanical indexes we separated the discussion into two parts: biomechanical analysis and EEG analysis.

Biomechanical analysis discussion

Trajectory results show that right-handers moved less with their non-dominant hand in the drawing task. Since this task lacked specific criteria for displacement, this suggests that right-handers intentionally chose to draw with less movement within the allotted time, similar result found by Aoki et al. (2016).

This aligns with their higher mean velocity when using the dominant hand in both tasks, behavior also founded by Borod et al. (1984). For left-handers, however, this behavior was observed only during writing tasks, highlighting a less lateralized motor strategy in this group. These findings are consistent with previous studies, such as those by Serrien & Sovijärvi-Spapé (2016) and Nelson, Berthier, & Konidaris (2018), which identified right-handers as more reliant on their dominant hand for fine motor tasks. This lateralized behavior likely reflects an adaptive strategy in right-handers, where the dominant hand is optimized for precision, while the non-dominant hand plays a supportive role.

In the writing task, both left- and right-handers required more elements (N_e) to complete the task with their non-dominant hand but produced these elements more quickly (N_{eps}) with their dominant hand. When no time constraints were imposed, participants performed the task more slowly with the non-dominant hand. Interestingly, left-handers exhibited a significantly higher W value when writing with the non-dominant hand compared to the dominant hand. Similar behavior was observed in right-handers in impedance control movements (higher W in the dominant hand). According to Fonseca et al. (2019), lower N_e and W values are indicative of skill acquisition and adaptation. This suggests that left-handers have a more hand-independent skill background for impedance control and right-handers for fine motor tasks. In both cases the right hand is responsible for the most skillful movement. Left-handers may have developed enhanced motor efficiency in their non-dominant hand to adapt to societal tools and environments predominantly designed for right-hand use. This interpretation aligns with qualitative reports from left-handed participants during recruitment, who frequently noted challenges in adapting to right-hand-oriented tools.

The α index further highlighted task-dependent differences, with significant ANOVA results indicating that α is sensitive to task demands, providing new features to Miranda (2018) that only found a standard value of α . Right-handers displayed lateralized behavior, with α values for writing with the dominant hand being close to $2/3$, while values for the non-dominant hand were much further away. Moreover, left-handers, showed no significant differences between hands, but their α values for both hands fell within a middle range, neither as close to $2/3$ as the right-hander's dominant hand nor as far as their non-dominant hand (see Table 5.2). These results point to a specialized adaptation in right-handers for writing with the dominant hand. While we were unable to calculate α for impedance control movements, left-handers showed significant differences in N_e values between hands. This indicates that they produce fewer impedance control elements with the right hand while writing, further supporting the idea that left-handers rely on unique neural strategies for stability and motor adaptation, while right-handers have a more accurate movement with the dominant hand (Sainburg, 2014; Serrien & Sovijärvi-Spapé, 2016).

EEG analysis discussion

The writing task performed with the dominant hand generated significantly lower cognitive load in the contralateral motor area, which is referenced in the literature as the dominant hemisphere of the brain (Papadatou-Pastou et al., 2020). This reflects the habitual practice of this group, composed of university students who are used to writing with their dominant hand but not to drawing or using the non-dominant hand for such tasks, which therefore demands greater cognitive effort. This is highlighted by comparisons showing that writing with the dominant hand places less cognitive load on the left temporal lobe than tasks performed with the non-dominant hand, which is possibly related to memory processes (Squire, 2004). In the group of left-handed participants, differences were observed between dominant and non-dominant hand use, with predominant activation in the parietal regions, areas associated with postural stability and impedance control during motor tasks (Shadmehr & Krakauer, 2008). Both right-handed and left-handed individuals showed decreased cognitive load when comparing drawing with the dominant versus non-dominant hand, which may be linked to structural differences in stability and impedance control during unconstrained movements (Sainburg, 2002; Yadav & Sainburg, 2011).

Summarizing

Drawing tasks show no significant differences between hands in α , W, Ne, and Neps biomechanical measures, likely due to the task's free nature, where the focus is on the creative process rather than performance. Our results suggest that the motor aspects of creativity do not depend on the hand used. In contrast, cognitive load differs between drawing with the dominant and non-dominant hand, indicating that the creative process is driven more by brain activity than by motor execution.

In summary, these results highlight fundamental differences in motor strategies between left- and right-handers. Right-handers optimize their dominant hand for writing precision and efficiency, while left-handers demonstrate a more adaptive approach, emphasizing impedance control. Both groups rely on the right hand, but for distinct purposes: writing in right-handers and stability in left-handers. These findings provide insight into the neural and biomechanical underpinnings of handedness and task performance.

5.5. Conclusion

By combining simple and complex biomechanical measurements, we provided a comprehensive motor characterization of handedness differences, achieving a depth of analysis not previously documented. Comparing these findings with EEG data, we concluded that right-handers exhibit greater lateralization for fine motor tasks, such as writing. In contrast, left-handers show a stronger lateralization for impedance control movements. Regardless of handedness, the right hand emerges as a critical contributor to motor tasks. Our results offer a nuanced interpretation of complex indices related to the handedness phenomenon, opening new possibilities for developing advanced rehabilitation tools for upper limb injuries with different approaches in left-handers or right-handers. Additionally, this work enhances our understanding of motor control in left-handers, particularly their unique association with impedance control movements. This work still lacks an approach focused on ambidextrous, and it must be improved using other indexes and tools.

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6. SUPPLEMENTARY MATERIAL 1-A

6.1. Collection setup

Data collection was conducted with 70 participants. The preparation for each session lasted approximately 1 hour and 30 minutes per subject, including room setup, research surveys (ICF, EHI and MINI mental test), equipment calibration, and the application of the EEG cap with conductive gel. Of this total time, only about 20 minutes were dedicated to data recording, including instructions between one task and another.

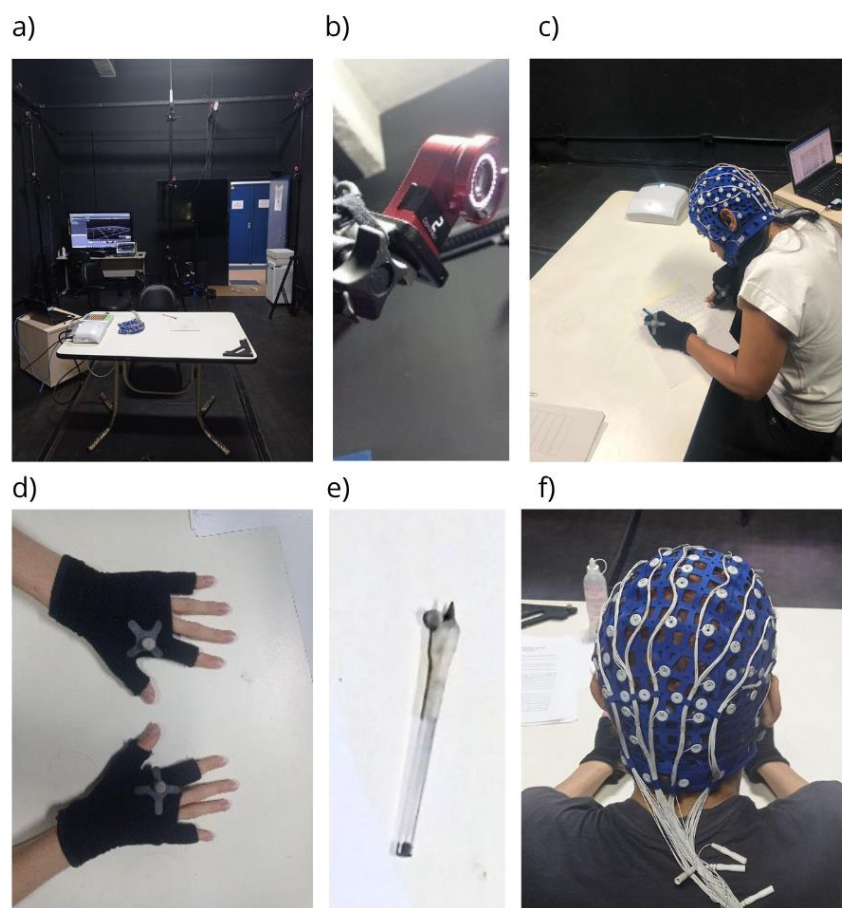


Figure 6.1: a) Room setup; b) One of the 17 cameras; c) Collection setup; d) Sensor positions on the glove; e) Sensor position on the tip of the pen; f) EEG cap.

In this study, data collection was conducted in a room specifically set up for three-dimensional analysis (MOCAP room, see Figure 6.1-a), located at the Dance School on the campus of the

Federal University of Bahia. We used a 3D motion capture (MoCap) device with 17 cameras (See Figure 6.1-b), which allows for the precise recording and analysis of dynamic body movements in three-dimensional space with 1 mm error. This technology is widely used in fields such as biomechanics, sports science, and animation. The core principle of 3D MoCap systems involves accurately tracking a subject's movement, typically through optical, marker-based systems that capture positional data with high temporal and spatial resolution. Before conducting the experiments, it was necessary to calibrate the motion capture equipment—a process that takes approximately 15 minutes. Calibration involves using a rod fitted with three sensors to systematically cover the entire capture volume. The quality of this spatial coverage directly influences the accuracy of the measurements, which are evaluated using qualitative indicators: poor, good, very good, perfect, and exceptional. All calibrations for this study were performed to achieve at least the "perfect" level, with most reaching the "exceptional" standard. The subjects were equipped with EEG cap, gloves on which the motion sensors were positioned. Another sensor was positioned on the tip of the pen used. All subjects participated of both biomechanical and EEG collection (see Figure 6.1- d, e and f).

6.2. Biomechanical data processing

First, movements were captured using the MOTIVE software, part of the MoCap system. From this software, we extracted the data recorded for each sensor and grouped the signals into markers. It is important to note that some data may appear duplicated or split between two sensors—this usually happens when a frame is lost and the software fails to recognize consecutive readings as coming from the same sensor.

After this step, the data were saved in .c3d files and processed in MATLAB. During this processing, we applied an axis correction, as the MED system was designed to segment trajectories into movements aligned with the XY plane. Therefore, the trajectories were rotated based on a leveling square placed on the table (see Figure 6.1-a), ensuring alignment with the X, Y, and Z axes.

Following the rotation, all the variables used in the study (as described in Section 1-2.2) were calculated. Finally, the data were classified according to hand dominance (dominant or non-

dominant hand) and participant group (right-handed, left-handed, or ambidextrous) for each variable. After classification, we conducted the statistical analyses using SPSS software. (See Figure 6.2)

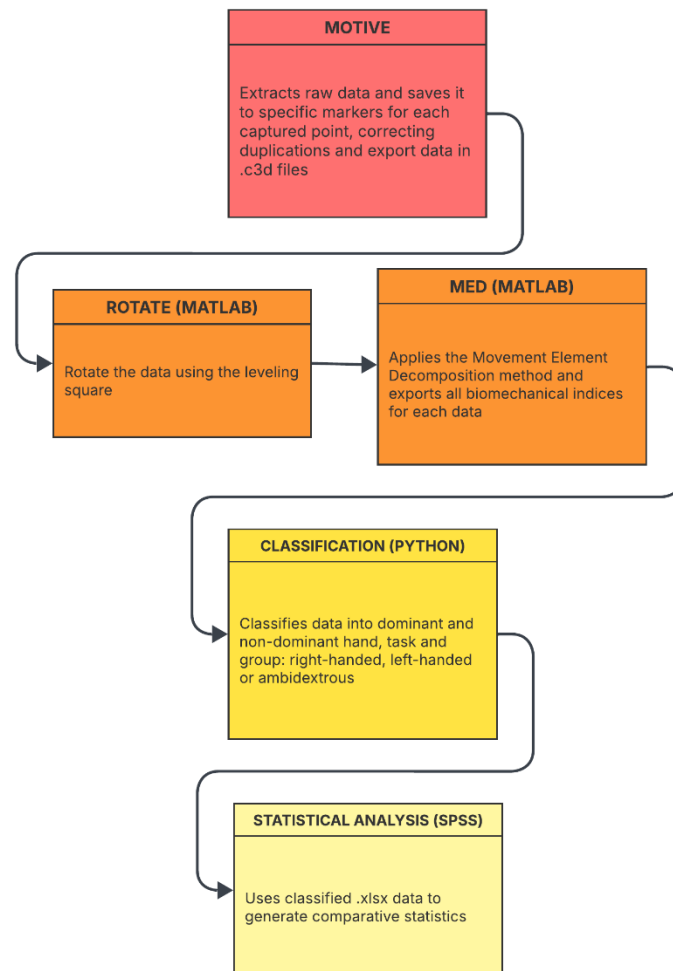


Figure 6.2: Processing the biomechanical data

6.3. EEG data processing

During the experiment, we collected a single EEG recording per session. This recording contained multiple labels marking the start and end of each task. The first processing step

involved using Profusion 6 software to segment the EEG file into separate tasks, based on the labels defined during data acquisition.

After segmentation, the data were exported in .EDF format and processed in MATLAB. Initially, we applied Independent Component Analysis (ICA) to remove artifacts. Following ICA, we conducted an additional artifact rejection step, excluding any EEG segments where the signal amplitude exceeded 200 μV . This threshold was established based on empirical observations from pilot studies, where signals above this level were typically associated with muscle activity, which is not the focus of this research. When high-amplitude artifacts were detected, we removed the corresponding 1-second window from the data.

After artifact removal, we calculated the spectral power of the EEG signals within the beta frequency band, averaging the power values by brain region. Finally, the processed data were exported as an .xlsx file for statistical analysis in SPSS. (See Figure 6.3).

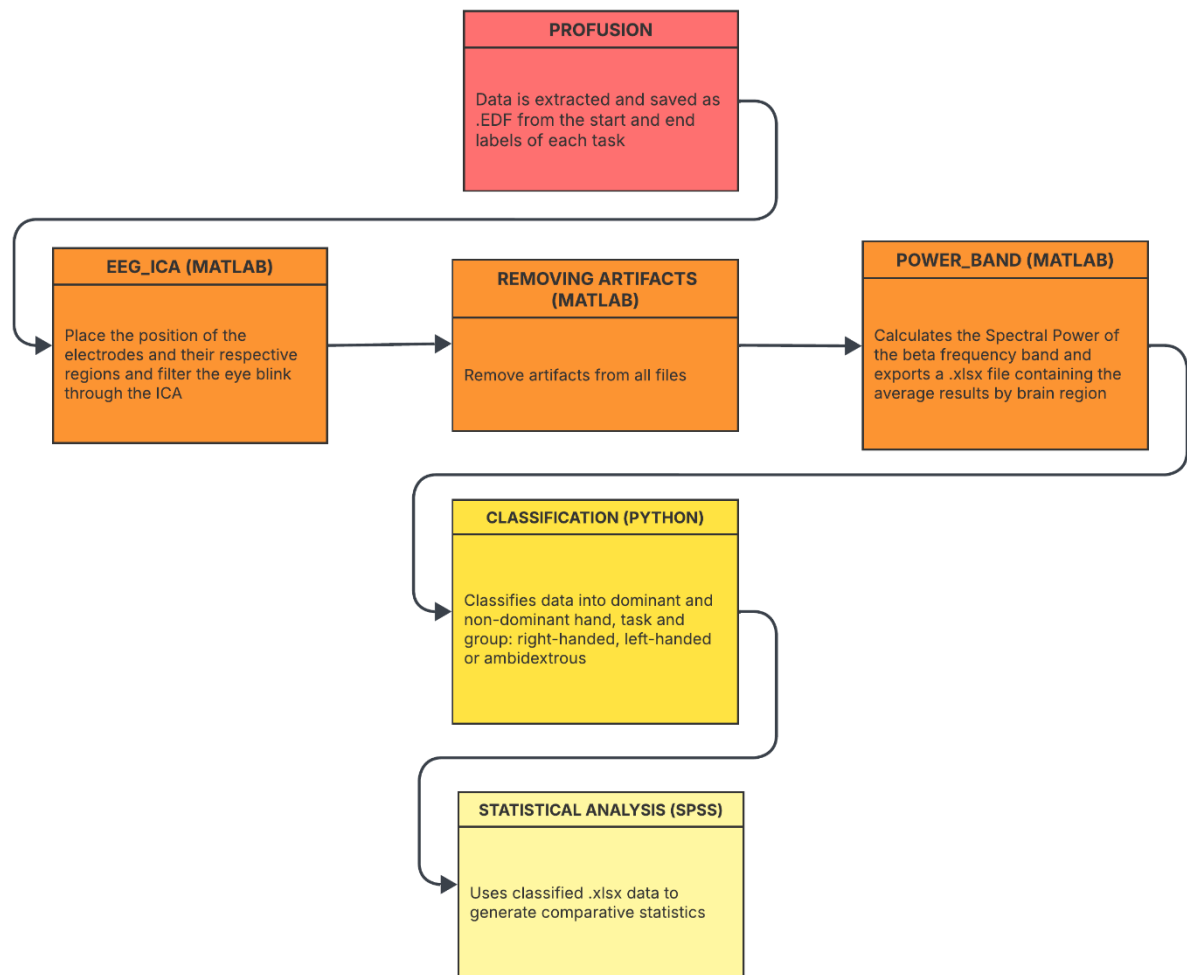


Figure 6.3: Processing the EEG data

7. SUPPLEMENTARY MATERIAL 1-B

ERD/S – thre way ANOVA - Post Hoc - comparisons between dominant and non-dominant hands (Bonferroni correction)							
Group	Region	Task I	Task J	Mean(ERD/S task I) + SE	Mean(ERD/S task J) + SE	Mean Difference (I-J)	p value
LH	RF	WR_DH	WR_NDH	-0.318±0.528	-0.580±0.602	.262	.495
			DR_DH	-0.318±0.528	-0.310±0.422	-.008	1.000
			DR_NDH	-0.318±0.528	-0.394±0.514	.076	1.000
		WR_NDH	DR_DH	-0.580±0.602	-0.310±0.422	-.270	1.000
			DR_NDH	-0.580±0.602	-0.394±0.514	-.186	1.000
			DR_NDH	-0.310±0.422	-0.394±0.514	.084	1.000
	LF	WR_DH	WR_NDH	-0.451±0.508	-0.481±0.501	.030	1.000
			DR_DH	-0.451±0.508	-0.178±0.401	-.272	.609
			DR_NDH	-0.451±0.508	-0.803±0.790	.352	1.000
		WR_NDH	DR_DH	-0.481±0.501	-0.178±0.401	-.303	.332
			DR_NDH	-0.481±0.501	-0.803±0.790	.322	1.000
			DR_NDH	-0.178±0.401	-0.803±0.790	.625	.826
	RC	WR_DH	WR_NDH	0.113±0.064	0.006±0.060	.108	.217
			DR_DH	0.113±0.064	0.157±0.047	-.044	1.000
			DR_NDH	0.113±0.064	0.142±0.051	-.028	1.000
		WR_NDH	DR_DH	0.006±0.060	0.157±0.047	-.152*	.003
			DR_NDH	0.006±0.060	0.142±0.051	-.136*	.018
			DR_NDH	0.157±0.047	0.142±0.051	.016	1.000
	LC	WR_DH	WR_NDH	0.033±0.074	-0.026±0.053	.059	1.000
			DR_DH	0.033±0.074	0.044±0.038	-.011	1.000
			DR_NDH	0.033±0.074	0.145±0.036	-.113	.527
		WR_NDH	DR_DH	-0.026±0.053	0.044±0.038	-.070	.988
			DR_NDH	-0.026±0.053	0.145±0.036	-.171*	.018
			DR_NDH	0.044±0.038	0.145±0.036	-.102*	.045
	RT	WR_DH	WR_NDH	0.406±0.295	0.005±0.590	.401	1.000
			DR_DH	0.406±0.295	0.697±0.350	-.291	.574
			DR_NDH	0.406±0.295	-0.101±0.275	.507*	.010
		WR_NDH	DR_DH	0.005±0.590	0.697±0.350	-.692	.733
			DR_NDH	0.005±0.590	-0.101±0.275	.107	1.000
			DR_NDH	0.697±0.350	-0.101±0.275	.799*	.022
	LT	WR_DH	WR_NDH	-0.346±0.158	-0.286±0.199	-.061	1.000
			DR_DH	-0.346±0.158	-0.408±0.183	.062	1.000
			DR_NDH	-0.346±0.158	-0.088±0.188	-.258	.805
		WR_NDH	DR_DH	-0.286±0.199	-0.408±0.183	.122	1.000
			DR_NDH	-0.286±0.199	-0.088±0.188	-.197	1.000
			DR_NDH	-0.408±0.183	-0.088±0.188	-.320	.086
	RP	WR_DH	WR_NDH	-0.012±0.051	-0.195±0.055	.183*	.008
			DR_DH	-0.012±0.051	0.030±0.046	-.042	1.000
			DR_NDH	-0.012±0.051	-0.031±0.046	.019	1.000
		WR_NDH	DR_DH	-0.195±0.055	0.030±0.046	-.225*	.000
			DR_NDH	-0.195±0.055	-0.031±0.046	-.164*	.026
			DR_NDH	0.030±0.046	-0.031±0.046	.061	.383
	LP	WR_DH	WR_NDH	-0.134±0.056	-0.096±0.054	-.038	1.000
			DR_DH	-0.134±0.056	-0.085±0.050	-.049	1.000
			DR_NDH	-0.134±0.056	0.065±0.040	-.199*	.009
		WR_NDH	DR_DH	-0.096±0.054	-0.085±0.050	-.011	1.000
			DR_NDH	-0.096±0.054	0.065±0.040	-.161*	.009
			DR_NDH	-0.085±0.050	0.065±0.040	-.150*	.002
	RO	WR_DH	WR_NDH	-0.843±0.359	-1.095±0.425	.252	.215
			DR_DH	-0.843±0.359	-0.829±0.545	-.013	1.000
			DR_NDH	-0.843±0.359	-0.833±0.471	-.009	1.000
		WR_NDH	DR_DH	-1.095±0.425	-0.829±0.545	-.266	.781

AM			DR_NDH	-1.095±0.425	-0.833±0.471	-.262	.150	
			DR_DH	DR_NDH	-0.829±0.545	-0.833±0.471	.004	1.000
	LO	WR_DH	WR_NDH	-0.628±0.392	-0.679±0.313	.051	1.000	
			DR_DH	-0.628±0.392	-0.665±0.315	.037	1.000	
			DR_NDH	-0.628±0.392	-0.501±0.333	-.128	1.000	
		WR_NDH	DR_DH	-0.679±0.313	-0.665±0.315	-.014	1.000	
			DR_NDH	-0.679±0.313	-0.501±0.333	-.179	.670	
		DR_DH	DR_NDH	-0.665±0.315	-0.501±0.333	-.164	1.000	
	RF	WR_DH	WR_NDH	0.169±0.807	0.231±0.920	-.062	1.000	
			DR_DH	0.169±0.807	0.139±0.644	.031	1.000	
			DR_NDH	0.169±0.807	0.097±0.785	.073	1.000	
		WR_NDH	DR_DH	0.231±0.920	0.139±0.644	.093	1.000	
			DR_NDH	0.231±0.920	0.097±0.785	.134	1.000	
		DR_DH	DR_NDH	0.139±0.644	0.097±0.785	.042	1.000	
	LF	WR_DH	WR_NDH	0.141±0.775	0.230±0.766	-.089	1.000	
			DR_DH	0.141±0.775	-0.114±0.613	.255	1.000	
			DR_NDH	0.141±0.775	0.035±1.207	.106	1.000	
		WR_NDH	DR_DH	0.230±0.766	-0.114±0.613	.344	.902	
			DR_NDH	0.230±0.766	0.035±1.207	.195	1.000	
		DR_DH	DR_NDH	-0.114±0.613	0.035±1.207	-.150	1.000	
	RC	WR_DH	WR_NDH	0.010±0.097	-0.033±0.092	.042	1.000	
			DR_DH	0.010±0.097	-0.039±0.072	.048	1.000	
			DR_NDH	0.010±0.097	-0.013±0.079	.022	1.000	
		WR_NDH	DR_DH	-0.033±0.092	-0.039±0.072	.006	1.000	
			DR_NDH	-0.033±0.092	-0.013±0.079	-.020	1.000	
		DR_DH	DR_NDH	-0.039±0.072	-0.013±0.079	-.026	1.000	
	LC	WR_DH	WR_NDH	-0.070±0.113	-0.068±0.081	-.001	1.000	
			DR_DH	-0.070±0.113	-0.126±0.059	.057	1.000	
			DR_NDH	-0.070±0.113	-0.039±0.054	-.030	1.000	
		WR_NDH	DR_DH	-0.068±0.081	-0.126±0.059	.058	1.000	
			DR_NDH	-0.068±0.081	-0.039±0.054	-.029	1.000	
		DR_DH	DR_NDH	-0.126±0.059	-0.039±0.054	-.087	.748	
	RT	WR_DH	WR_NDH	-0.246±0.450	-0.590±0.901	.344	1.000	
			DR_DH	-0.246±0.450	-0.313±0.534	.067	1.000	
			DR_NDH	-0.246±0.450	-0.508±0.420	.262	1.000	
		WR_NDH	DR_DH	-0.590±0.901	-0.313±0.534	-.277	1.000	
			DR_NDH	-0.590±0.901	-0.508±0.420	-.082	1.000	
		DR_DH	DR_NDH	-0.313±0.534	-0.508±0.420	.195	1.000	
	LT	WR_DH	WR_NDH	-0.560±0.241	-0.424±0.304	-.136	1.000	
			DR_DH	-0.560±0.241	-0.613±0.279	.052	1.000	
			DR_NDH	-0.560±0.241	-0.336±0.287	-.225	1.000	
		WR_NDH	DR_DH	-0.424±0.304	-0.613±0.279	.189	1.000	
			DR_NDH	-0.424±0.304	-0.336±0.287	-.089	1.000	
		DR_DH	DR_NDH	-0.613±0.279	-0.336±0.287	-.277	.940	
	RP	WR_DH	WR_NDH	-0.064±0.079	-0.144±0.084	.079	1.000	
			DR_DH	-0.064±0.079	-0.055±0.070	-.009	1.000	
			DR_NDH	-0.064±0.079	-0.114±0.070	.050	1.000	
		WR_NDH	DR_DH	-0.144±0.084	-0.055±0.070	-.089	1.000	
			DR_NDH	-0.144±0.084	-0.114±0.070	-.029	1.000	
		DR_DH	DR_NDH	-0.055±0.070	-0.114±0.070	.059	1.000	
	LP	WR_DH	WR_NDH	-0.173±0.086	-0.120±0.083	-.053	1.000	
			DR_DH	-0.173±0.086	-0.207±0.077	.034	1.000	
			DR_NDH	-0.173±0.086	-0.093±0.062	-.080	1.000	
		WR_NDH	DR_DH	-0.120±0.083	-0.207±0.077	.087	1.000	
			DR_NDH	-0.120±0.083	-0.093±0.062	-.027	1.000	
		DR_DH	DR_NDH	-0.207±0.077	-0.093±0.062	-.115	.361	
	RO	WR_DH	WR_NDH	-0.883±0.548	-0.999±0.649	.116	1.000	
			DR_DH	-0.883±0.548	-0.757±0.832	-.126	1.000	
		DR_NDH	-0.883±0.548	-0.851±0.720	-.032	1.000		

RH	LO	WR_NDH	DR_DH	-0.999±0.649	-0.757±0.832	-.241	1.000
			DR_NDH	-0.999±0.649	-0.851±0.720	-.148	1.000
		DR_DH	DR_NDH	-0.757±0.832	-0.851±0.720	.094	1.000
		WR_DH	WR_NDH	-0.861±0.598	-0.757±0.479	-.104	1.000
	RF		DR_DH	-0.861±0.598	-0.925±0.481	.064	1.000
			DR_NDH	-0.861±0.598	-0.688±0.509	-.172	1.000
		WR_NDH	DR_DH	-0.757±0.479	-0.925±0.481	.168	1.000
			DR_NDH	-0.757±0.479	-0.688±0.509	-.068	1.000
	LF	DR_DH	DR_NDH	-0.925±0.481	-0.688±0.509	-.236	1.000
		WR_DH	WR_NDH	0.361±0.475	0.634±0.541	-.273	.273
			DR_DH	0.361±0.475	0.113±0.379	.249	1.000
			DR_NDH	0.361±0.475	0.528±0.462	-.167	1.000
	RC	WR_NDH	DR_DH	0.634±0.541	0.113±0.379	.521	.620
			DR_NDH	0.634±0.541	0.528±0.462	.106	1.000
		DR_DH	DR_NDH	0.113±0.379	0.528±0.462	-.415	.157
		WR_DH	WR_NDH	-0.007±0.456	0.049±0.451	-.055	1.000
	LC		DR_DH	-0.007±0.456	0.099±0.361	-.106	1.000
			DR_NDH	-0.007±0.456	0.166±0.710	-.173	1.000
		WR_NDH	DR_DH	0.049±0.451	0.099±0.361	-.051	1.000
			DR_NDH	0.049±0.451	0.166±0.710	-.117	1.000
	RT	DR_DH	DR_NDH	0.099±0.361	0.166±0.710	-.067	1.000
		WR_DH	WR_NDH	-0.084±0.057	-0.005±0.054	-.080	.499
			DR_DH	-0.084±0.057	-0.048±0.042	-.037	1.000
			DR_NDH	-0.084±0.057	0.014±0.046	-.098	.146
	LT	WR_NDH	DR_DH	-0.005±0.054	-0.048±0.042	.043	1.000
			DR_NDH	-0.005±0.054	0.014±0.046	-.019	1.000
		DR_DH	DR_NDH	-0.048±0.042	0.014±0.046	-.061	.230
		WR_DH	WR_NDH	0.384±0.066	-0.061±0.048	.445*	.000
	RP		DR_DH	0.384±0.066	-0.010±0.034	.394*	.000
			DR_NDH	0.384±0.066	-0.050±0.032	.434*	.000
		WR_NDH	DR_DH	-0.061±0.048	-0.010±0.034	-.051	1.000
			DR_NDH	-0.061±0.048	-0.050±0.032	-.011	1.000
	LP	DR_DH	DR_NDH	-0.010±0.034	-0.050±0.032	.040	1.000
		WR_DH	WR_NDH	-0.670±0.265	-0.435±0.530	-.235	1.000
			DR_DH	-0.670±0.265	-0.603±0.314	-.067	1.000
			DR_NDH	-0.670±0.265	-0.389±0.247	-.282	.272
	RO	WR_NDH	DR_DH	-0.435±0.530	-0.603±0.314	.168	1.000
			DR_NDH	-0.435±0.530	-0.389±0.247	-.046	1.000
		DR_DH	DR_NDH	-0.603±0.314	-0.389±0.247	-.214	1.000
		WR_DH	WR_NDH	-0.315±0.142	-0.587±0.179	.273*	.049
	RP		DR_DH	-0.315±0.142	-0.342±0.164	.027	1.000
			DR_NDH	-0.315±0.142	-0.819±0.169	.505*	.010
		WR_NDH	DR_DH	-0.587±0.179	-0.342±0.164	-.245	.206
			DR_NDH	-0.587±0.179	-0.819±0.169	.232	.650
	LP	DR_DH	DR_NDH	-0.342±0.164	-0.819±0.169	.477*	.001
		WR_DH	WR_NDH	-0.221±0.046	-0.119±0.049	-.102	.238
			DR_DH	-0.221±0.046	-0.177±0.041	-.043	1.000
			DR_NDH	-0.221±0.046	-0.078±0.041	-.142*	.004
	LP	WR_NDH	DR_DH	-0.119±0.049	-0.177±0.041	.059	1.000
			DR_NDH	-0.119±0.049	-0.078±0.041	-.040	1.000
		DR_DH	DR_NDH	-0.177±0.041	-0.078±0.041	-.099*	.007
		WR_DH	WR_NDH	-0.123±0.051	-0.182±0.049	.059	1.000
	LP		DR_DH	-0.123±0.051	-0.064±0.045	-.059	1.000
			DR_NDH	-0.123±0.051	-0.175±0.036	.052	1.000
		WR_NDH	DR_DH	-0.182±0.049	-0.064±0.045	-.118*	.031
			DR_NDH	-0.182±0.049	-0.175±0.036	-.007	1.000
	RO	DR_DH	DR_NDH	-0.064±0.045	-0.175±0.036	.111*	.015
		WR_DH	WR_NDH	-0.681±0.323	-0.506±0.382	-.175	.612
			DR_DH	-0.681±0.323	-0.471±0.490	-.210	1.000

			DR_NDH	-0.681±0.323	-0.461±0.424	-.220	.742
WR_NDH			DR_DH	-0.506±0.382	-0.471±0.490	-.035	1.000
			DR_NDH	-0.506±0.382	-0.461±0.424	-.045	1.000
DR_DH			DR_NDH	-0.471±0.490	-0.461±0.424	-.010	1.000
LO	WR_DH	WR_NDH	DR_NDH	-0.624±0.352	-1.076±0.282	.452	.098
		DR_DH	DR_NDH	-0.624±0.352	-0.819±0.283	.195	.998
		DR_NDH	DR_NDH	-0.624±0.352	-1.055±0.299	.430	.181
	WR_NDH	DR_DH	DR_NDH	-1.076±0.282	-0.819±0.283	-.257*	.020
			DR_NDH	-1.076±0.282	-1.055±0.299	-.022	1.000
DR_DH			DR_NDH	-0.819±0.283	-1.055±0.299	.235	.187

*. The mean difference is significant at the .05 level.

Adjustment for multiple comparisons: Bonferroni.

Table 7.1: EEG measurements by region, comparison between task-hand

8. PAPER 2

Linking Biomechanical Model Dynamics and Neural Complexity: Permutation Entropy Approaches to Motor Control

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Fernanda Selingardi Matias⁸ and José Garcia Vivas Miranda¹.

ABSTRACT

This study presents a novel complexity-based framework integrating neural and biomechanical perspectives to assess motor asymmetry and brain lateralization. Using principles from non-linear dynamics and information theory, we model motor output by treating the biomechanical scaling exponent α (from a velocity-displacement power law found in human movement data: $\bar{v} \propto D^\alpha$) as a time-varying marker of control strategy. Sixty-three participants (right-, left-handed, and ambidextrous) performed writing and drawing tasks with both hands. Biomechanical data were decomposed into sub-movements, generating α time series whose temporal diversity was quantified using Permutation Entropy (PE). PE analysis was applied to EEG signals as well, in order to assess neural dynamics patterns across time scales. Analysis showed higher PE in biomechanical dominant-hand movement data, reflecting richer motor variability related to more degrees of freedom. EEG results indicate that right-handers displayed shorter time reaction differences between hands during handwriting. Left-handers and ambidextrous individuals showed task-independent asymmetry. Time series patterns suggest that right-handers are not genuinely more hand-dependent, but less familiar with left hand use. By linking time-evolving motor output and neural control through entropy measures, this approach offers a sensitive tool for studying motor control, with implications for neuroscience, motor learning, and rehabilitation.

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Keywords: Permutation Entropy, Complexity, Handedness, Movement Element Decomposition, Motor Control.

8.1. Introduction

Hand preference is a fundamental aspect of motor control that shapes how individuals interact with their environment. It significantly influences the development of fine motor abilities (Nalçacı et al., 2001; Arndt et al., 2003; Yetkin et al., 2012; Parish et al., 2013; Mentese et al., 2024) and cognitive processes (Nicholls et al., 2010; Somers et al., 2015; Prichard et al., 2013). Handedness has been shown to affect both the efficiency and variability of motor execution. Right-handed individuals typically exhibit stronger lateralization of motor control, with a predominant role of the left hemisphere. In contrast, left-handers often display more symmetrical cortical engagement, suggesting a less hand-dependent motor and neural behavior (Judge & Stirling, 2003; Goble & Brown, 2008). However, this apparent asymmetry may be biased by environmental factors. Since most tools and daily objects are designed for right-hand use, left-handers and ambidextrous individuals are frequently required to engage their non-dominant hand for simple tasks, which may increase their adaptability and reduce asymmetry in motor performance in simple motor tasks (Yetkin et al., 2012; Lajtos, Barradas-Chacón, & Wriessnegger, 2023). In this study, we introduce tasks that challenge both hands under unfamiliar and demanding conditions—specifically, writing and drawing. These activities are rarely performed with the non-dominant hand in everyday life and are expected to provide valuable insights into motor asymmetry and cortical lateralization.

Tasks performed with the non-dominant hand or under unfamiliar configurations often result in more rigid, repetitive, and predictable movements, reflecting limited motor control and fewer available solutions (Gray, 2020; Guimarães et al., 2020; Latash, 2010; Vereijken, 1992). This stereotyped execution is likely to manifest in the underlying signal dynamics as reduced variability and complexity, whereas dominant-hand movements may display a richer motor repertoire. According to complexity science, this translates to higher signal complexity and entropy in the dominant hand, as opposed to lower entropy in the non-dominant hand (Stergiou & Decker, 2011; Hsu et al., 2017). We use Permutation Entropy (PE) to evaluate the

randomness of motor strategies during fine motor tasks. Lower PE values indicate greater regularity and predictability, often associated with reduced flexibility or increased control effort. Conversely, higher entropy reflects a greater diversity of motor strategies and less stereotyped behavior.

From a neural perspective, we analyze EEG time-series data to investigate how brain dynamics shift during hand switching. Specifically, we focus on cortical regions implicated in balance, stability, and limb impedance control, primarily the parietal lobe (Ehrsson et al., 2000; Hülzdünker et al., 2015; Milner et al., 2006). Variations in PE across these regions can serve as indicators of neural asymmetry in stability, where higher entropy signals more unpredictable, resource-demanding brain activity. To assess how hand dependency influences predictability in motor tasks, we designed two experiments: one involving a neutral word writing task and another involving creative drawing. While writing emphasizes fine motor accuracy and may reveal stronger lateralization, drawing focuses more on creative expression and less on motor precision, potentially resulting in less asymmetrical cortical dynamics when comparing hands. Previous studies with right-handed individuals have shown a strong dominance of the right hemisphere during creative tasks such as drawing (Mihov et al., 2010; Belkofer, et al. 2014), and a left-hemisphere dominance during fine motor tasks (Ehrsson et al., 2000) such as writing. In this study, we aim to extend this analysis to include left-handers and ambidextrous individuals, to investigate whether similar hemispheric patterns are preserved across different handedness profiles.

Studies have shown that the delay parameter τ in PE is associated with the temporal scales of neural processing, reflecting features such as sensorimotor response time (Watanabe et al., 2019). When comparing two tasks across different τ values, it is possible to identify the τ that maximizes the entropy difference, revealing the temporal scale most discriminative of the underlying behaviors (Myers et al., 2020; Buccellato et al., 2023).

A larger optimal τ is often linked to tasks that require greater control and precision, such as fine motor actions, whereas a smaller τ indicates sensitivity to faster, more automatic dynamics, as typically found in gross motor tasks (Waschke et al., 2021).

When comparing familiar and unfamiliar movements, studies have shown that the brain's response time tends to be longer for unfamiliar motor tasks (Debaere et al., 2004; Floyer-Lea & Matthews, 2005). Based on this, we hypothesize that computing different time scales of Permutation Entropy may reveal differences between hands at shorter temporal scales when gross motor difficulties are present, even in simple movements. By comparing different participant groups, we aim to investigate intermanual asymmetries and identify the specific temporal scales at which these differences emerge.

From a dynamical systems perspective, this experimental framework allows us to test three hypotheses:

1. **Systematic Motor Control Hypothesis:** Motor control emerges from the interaction between the brain and limb dynamics. Unfamiliar tasks require greater cerebral adaptation and produce more unpredictable behavior, generating more predictable outputs due to reduced motor repertoire (Krishnan et al., 2018).
2. **Task-Constraint Hypothesis:** Asymmetries in motor system dynamics relies on task constraints. Highly constrained tasks like writing are expected to generate greater entropic differences between hands than less constrained tasks like drawing.
3. **Controller-Output Hypothesis:** The state of the system's central controller (the brain) should reflect the dynamics of its output. We hypothesize that differences between dominant and non-dominant hand behavior will be more pronounced in individuals with greater hand-use asymmetry (right-handers). In contrast, left-handers and ambidextrous individuals, who routinely use both hands in daily life, are expected to show more ordinary neural differences.

8.2. Experimental data

Seventy participants were recruited for the study, encompassing right-handed, left-handed, and ambidextrous individuals, as classified by the Edinburgh Handedness Inventory (EHI) (Oldfield, 1971). Cognitive function was screened using the Mini-Mental State Examination (MMSE) to ensure the absence of cognitive impairments. Only individuals with no neurological disorders and a score above 25 on the MMSE (Cockrell & Folstein, 2002) were eligible to participate in the EEG recordings.

Brain signals were measured using a 64-channel Compumedics Neuroscan Neuvo EEG cap, with electrodes placed according to the International 10–10 system. Electrode impedance was kept below 60 k Ω throughout the recordings. Signal preprocessing included digitization and artifact correction using Independent Component Analysis (ICA), which allowed for the removal of common artifacts such as eye blinks and muscle activity (Jung et al., 2000). The sampling rate was set to 1000 Hz. While hand and pen-tip movements were tracked using an 120Hz OptiTrack Motion Capture system. The experimental protocol received approval from the Ethics Committee of the Faculty of Pharmacy at the Federal University of Bahia (Certificate of Presentation for Ethical Appreciation: 68289021.5.0000.5531), in accordance with the Declaration of Helsinki.

For statistical analysis, selected electrodes were grouped into regions of interest corresponding to major cortical areas, as follows:

- Right Frontal (FR): FP2, AF4, F10, F8, F6, F4
- Left Frontal (FL): FP1, AF3, F9, F7, F5, F3
- Right Central (CR): FC6, FC4, FC2, F2, C6, C4, C2
- Left Central (CL): FC5, FC3, FC1, F1, C5, C3, C1
- Right Temporal (TR): TP8, T8
- Left Temporal (TL): TP7, T7
- Right Parietal (PR): CP6, CP4, CP2, P10, P8, P6, P4, P2
- Left Parietal (PL): CP5, CP3, CP1, P9, P7, P5, P3, P1
- Right Occipital (OR): PO4, O2, CB2
- Left Occipital (OL): PO3, O1, CB1

The protocol was divided into three parts: baseline EEG recording, a writing task, and a free drawing task. Each task was performed once with each hand, with the order of hand used randomized. Participants were seated at a table with a pen and paper to complete the following activities (see Figure 8.1):

- **Writing Task (WR):** Participants wrote the word “bahia” in cursive in 24 printed boxes on an A4 sheet, using three different scales. Repetition parameters were determined through pilot testing to ensure a minimum of 120 seconds of EEG recording per condition.
- **Drawing Task (DR):** Participants were instructed to create a free drawing, realistic or abstract, on an A4 sheet of paper over 120 seconds. This task was also performed once with each hand.

All participants were healthy volunteers from the university community, including undergraduate and graduate students, technical staff, and faculty members. We selected individuals who reported regular writing habits and little to no engagement in drawing activities. No monetary compensation was provided.

Biomechanical collection			
	Left-handed	Ambidextrous	Right-handed
Female	27.5 ± 2.8 (12 subjects)	-	23.3 ± 3.7 (10 subjects)
Male	22.2 ± 1.3 (11 subjects)	29.1 ± 2.9 (9 subjects)	24.6 ± 1.3 (19 subjects)
EEG collection			
Female	27.9 ± 3.0 (11 subjects)	-	27.4 ± 7.2 (5 subjects)
Male	22.1 ± 1.4 (10 subjects)	29.1 ± 2.9 (9 subjects)	24.1 ± 1.2 (21 subjects)

Table 8.1: Mean age and standard deviation by handedness group and sex in collections.

After excluding low-quality data and participants who did not meet MMSE criteria, the final sample consisted of 63 individuals for the biomechanical analysis (30 right-handers, 10 ambidextrous, 23 left-handers) and 56 individuals for the EEG analysis (26 right-handers, 9 ambidextrous, 21 left-handers). The overall mean age of participants was 25.7 ± 8.3 years. (See Table 8. 1).

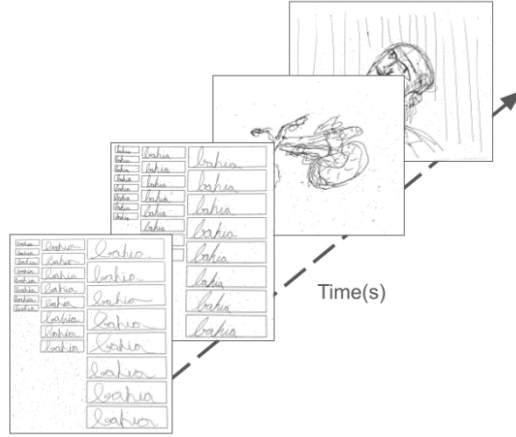


Figure 8.1: Example of experiment sequence: Writing with non-dominant hand; Writing with dominant hand; Drawing with non-dominant hand; Drawing with dominant hand.

8.3. Movement Element Decomposition method and it's applications

From the studies of Flash and Hogan (1985) on jerk minimization, Hoff (1994) proposed a model that also includes time in movement optimization, given by the minimization of I (see Eq. 8.1). In his work, Hoff minimizes the jerk (u) absolute value and time using the cost function in Eq. 8.1.

$$I = t_f + K \int_0^{t_f} (u_x^2 + u_y^2 + u_z^2) dt \quad (8.1)$$

Where t_f is time duration of the movement. Using this equation, Hoff found a bell-shaped curve the velocity with roots in $t=0$ and $t=t_f$ (Eq. 8.2) that according to Miranda et al. (2018) can be found in complex movements as well, when the movement is divided by zero-crossing of the velocity function in Cartesian coordinates, the entitled Movement Element Decomposition (MED) method.

$$v(t) = D \left[30 \frac{t^4}{t_f^5} - 60 \frac{t^3}{t_f^4} + 30 \frac{t^2}{t_f^3} \right] = D \cdot 30 \left(\frac{t}{t_f} \right)^2 \left(1 - \frac{t}{t_f} \right)^2 \quad (8.2)$$

Where D is the displacement. Using MED method, we divided the raw trajectory data into sub-movements separated by zero-crossings in the velocity function of x , y and z coordinates. These sub-movements have a relation between mean velocity $\bar{v}$ and displacement D (Miranda et al., 2018):

$$\bar{v} = \frac{D^\alpha}{(60K)^{\frac{1}{3}}} \quad (8.3)$$

Based on Hoff (1994) model, Miranda et al. (2018) found that the best equilibrium between minimization of jerk and time results in $\alpha = \frac{2}{3}$, finding also an experimental correspondence to this value. Using this approach, we have that α values higher than $2/3$, result in a motor strategy that emphasizes time minimization, while spending more jerk. In contrast, α values lower than $2/3$ emphasize jerk minimization, while spending more time.

Nikolai Bernstein (1967) introduced the concept that the human motor system has more degrees of freedom than strictly necessary for most tasks. This provides flexibility for movement strategies. This flexibility helps in distributing muscular effort and reducing unnecessary tension (Haywood & Getchell, 2024). From this perspective, we expect that in daily situations, α values change during tasks.

To measure how α patterns change, was computed the best log-log fit between mean velocity and displacement for sub-movements found in a slide window of 20 seconds length along the sample as displayed in Eq. 8.4. This generates a time series of alpha values. Then we calculated the permutation entropy of the time series of α values. Our method is sensitive to small changes in the pattern sequence.

$$\alpha_i = \left(\alpha_{\{0,20f\}}, \alpha_{\{1,(20f+1)\}}, \alpha_{\{2,(20f+2)\}}, \dots, \alpha_{\{(n-20f),n\}} \right) \quad (8.4)$$

Where n = number of movement frames recorded and f = sample rate.

8.4. Permutation Entropy

Permutation entropy (PE) has emerged as a powerful tool for assessing the predictability of time-series data in neural systems (Richman & Moorman, 2000; Costa et al., 2005). PE measures the unpredictability of the sequence of patterns, not of the occurrence of certain values, as Shannon entropy does. The highest value of entropy occurs when all states have the same probability. PE is commonly used to study neural signals time series (Cao et al., 2004; Da Paz et al., 2024), in our approach we applied PE to both EEG and Biomechanical complex data.

Permutation Entropy (PE) is a statistical measure introduced to quantify the complexity or degree of disorder in a time series. Unlike conventional entropy measures that rely on the actual

values of the signal, PE focuses on the ordinal patterns, or permutations, formed by comparing the relative magnitudes of neighboring values. This property makes PE particularly robust to noise, nonlinearities, and monotonic transformations, making it well-suited for analyzing complex dynamical systems.

To compute PE, one begins with a given time series $X = \{x_1, x_2, \dots, x_N\}$. The method involves reconstructing the time series into a set of overlapping vectors, often referred to as motifs, by selecting a fixed embedding dimension d and a time delay τ . Each motif is constructed as a vector of the form:

$$v_i = (x_i, x_{i+\tau}, x_{i+2\tau}, \dots, x_{i+(d-1)\tau}) \quad (8.5)$$

Where $i=1,2,\dots,N-(d-1)\tau$. This process effectively embeds the time series in a d -dimensional space, allowing one to examine its temporal structure. The next step involves determining the ordinal pattern of each motif. This is achieved by ranking the elements of each vector v_i in ascending order. Each unique ranking corresponds to one of the $d!$ possible permutations of distinct elements. For example, the motif (5.0, 3.3, 9.1) has the permutation pattern (2nd, 1st, 3rd), which corresponds to the permutation (1, 0, 2), see possible motifs for $d=3$ in Figure 8.2. This process is repeated for all valid indices i in the time series, thereby generating a sequence of permutation patterns.

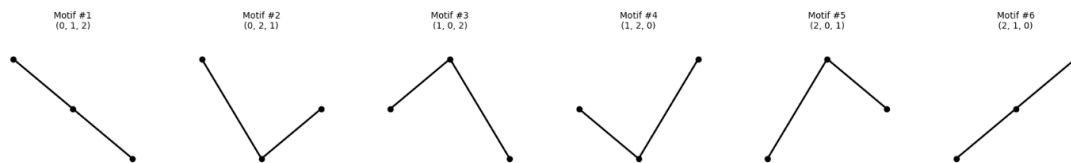


Figure 8.2: π_i possible configurations for $d=3$.

Once the permutation patterns have been extracted, their empirical frequencies are computed. Let $p(\pi_j)$ denote the relative frequency of the π_j -th permutation among all observed motifs, where $j=1,2,\dots,d!$. The Permutation Entropy is then defined using Shannon's entropy formula, normalized by the maximum possible entropy (which occurs when all permutations are equally likely):

$$PE_{(d,\tau)} = - \frac{1}{\log(d!)} \sum_{j=1}^{d!} p(\pi_j) * \log(p(\pi_j)) \quad (8.6)$$

This normalized value ranges from 0 (maximally regular) to 1 (maximally random).

The bell-shaped curve described by Eq. 8.2 has a minimum of three points. The first and the last are zeroes, meaning the starting and ending velocity of the movement by definition. In between them, there is a point of maximum for said velocity. Considering this, we can only admit motifs with $\tau \geq 2$. In this approach, we are considering $\tau = 2$ meanwhile EEG data was analysed for a range of τ values. In order to find the values of τ that characterize a complex dynamic we evaluated PE values across a range τ between 1ms and 50ms, similar parameters used by Da Paz et al. (2024) for task characterization. By calculating across a range of τ values, we can differentiate response time scales to motor activity, allowing us to distinguish between distinct neural components.

To keep comparable results between biomechanical tasks, we just consider the first 4000 frames, limiting the number to the minimum values of time in our sample. The same was done in the EEG data, considering the first 40000 frames. The total number of motifs is given by $d!$, for biomechanical samples we are using $d=5$, so there are 120 possible motifs. Due to the expressive difference of data frequency rate between biomechanical and EEG samples (EEG: 1000Hz and Biomechanical: 120Hz), we used $d=6$ for the EEG signals.

8.5. Asymmetry measurements

For analyze hand dependency, we are studying values of $\Delta PE = PE(DH) - PE(NDH)$, where DH is the data from dominant hand execution and NDH with the non-dominant hand execution. We are testing in which cases $PE(DH)$ and $PE(NDH)$ are significantly different for each handedness group.

While the distinction between dominant and non-dominant hands is clear for left- and right-handed individuals, it is not as straightforward for ambidextrous participants. Each ambidextrous individual tends to have a preferred and a non-preferred hand for writing and drawing. Therefore, in this study, we defined their dominant and non-dominant based on self-reported hand of preference during writing and drawing. (All ambidextrous declared a specific preferred hand for writing or drawing).

For hand dependency in different tasks we define the index Lateral Entropic Asymmetry (LEA):

$$LEA = \frac{PE(DH) - PE(NDH)}{PE(DH) + PE(NDH)} = \frac{\Delta PE}{PE(DH) + PE(NDH)} \quad (8.7)$$

This index will also be applied to biomechanical data to provide further insights into the lateralization of motor behavior across both tasks. The introduction of the normalized index LEA (Lateralization Entropy Asymmetry) is essential for comparing relative asymmetry between different experimental conditions, as it effectively accounts for baseline shifts in absolute PE values between tasks.

Due to the number of electrodes of EEG data, we employ an additional index to quantify overall lateralization: the Root Mean Square (RMS) of ΔPE . Unlike directional asymmetry measures, the $RMS(\Delta PE)$ captures the magnitude of asymmetry, offering a robust metric for assessing the intensity of lateralized activity. For the analysis we have average values of $\overline{\Delta PE_i}$ for each channel i . It's calculated by the average ΔPE for n subjects. Given a value of τ :

$$\overline{\Delta PE_i}(\tau) = \frac{1}{n} \sum_{j=1}^n \Delta PE_{ij}(\tau) \quad (8.8)$$

The RMS value is given for N channels is given by:

$$RMS_{\overline{\Delta PE}}(\tau) = \sqrt{\frac{1}{N} \sum_{i=1}^N \overline{\Delta PE_i}(\tau)^2} \quad (8.9)$$

For measure the error of this variable from the errors of $\overline{\Delta PE_i}$ values we use the approach given by (Jcgm; 2008):

$$\sigma_{RMS_{\overline{\Delta PE}}}(\tau) = \frac{1}{N \cdot RMS_{\overline{\Delta PE}}(\tau)} \sqrt{\sum_{i=1}^N \overline{\Delta PE_i}(\tau)^2 \cdot \sigma_{\overline{\Delta PE_i}}^2(\tau)} \quad (8.10)$$

$RMS_{\overline{\Delta PE}}(\tau)$ was used to quantify τ values with highest lateralization.

8.6. EEG Results

An initial characterization of permutation entropy (PE) as a function of τ reveals a power-law behavior at temporal scales below 8ms. Across electrodes and tasks, variations in PE values occur primarily at the third decimal place (see Figure 8.3), indicating a high degree of consistency within this regime. Such a scaling pattern is characteristic of nonlinear dynamics and is commonly associated with the behavior of complex systems exhibiting emergent properties.

Although robust characterization of scale-free behavior typically requires more than two decades of scale, the aim of this study is to demonstrate the applicability of the method rather than to confirm scale-free properties. This limitation in scale is not unusual; as Broido and Clauset (2019) point out, scale-free behavior in human-related phenomena often spans less than two decades of magnitude.

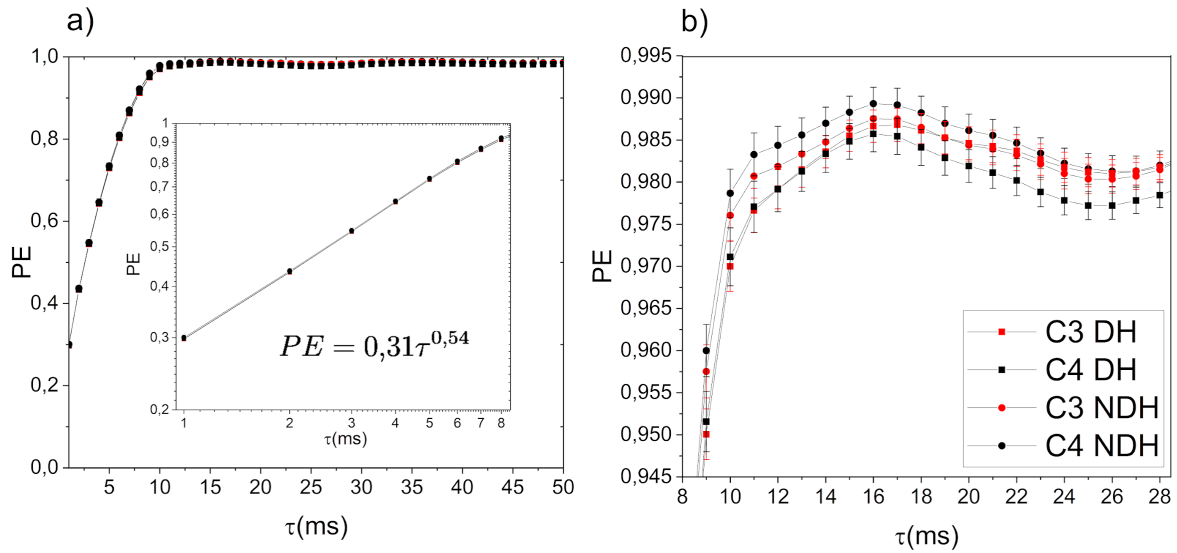


Figure 8.3: ΔPE in function of τ : a) Power-law behavior; b) Comparisons between C3 and C4 electrodes during writing with dominant (DH) and non-dominant hand (NDH).

Measuring $RMS_{\Delta PE}$ we found a high error, calculated by Eq. 8.10, it was expected due the different nature of electrodes, it doesn't invalidate the choice of most lateralized τ , once the lateralization process is not uniform. Results show that right-handers writing have higher values in $\tau = 4$ (See Figure 8.4-c), then only maximum value for $RMS_{\Delta PE}$ under a power-law behavior, meanwhile $RMS_{\Delta PE}$ for other tasks and groups are immediately after the power-law behavior. In all writing task conditions, ΔPE values were negative, indicating higher permutation entropy in the non-dominant hand. This suggests that writing with the non-dominant hand requires greater neural control and generates more complex cortical dynamics. In contrast, the drawing task did not show a general lateralization pattern, but localized mainly in the parietal ipsilateral area (see Figure 8.4-d,e and f), possibly reflecting region-specific engagement during less constrained and creative motor activity.

Higher values of $RMS_{\overline{\Delta PE}}$ in the complex dynamic regime are indicative of nonlinear behavior and the emergence of power-law patterns in brain activity. In contrast, values in the saturation region are associated with more random dynamics and a lack of complex patterns. In our results, right-handers exhibited higher ΔPE values within the power-law region, suggesting that the most distinguishable differences in hand use during writing tasks stem from the formation of complex temporal patterns. This may reflect the unfamiliarity of executing fine motor tasks with the non-dominant hand, which demands greater neural control. For right-handers and ambidextrous during writing task there is also have a secondary peak in $\tau = 15$ (see Figure 8.4-b and c), this data is well expanded and discussed in the supplementary material.

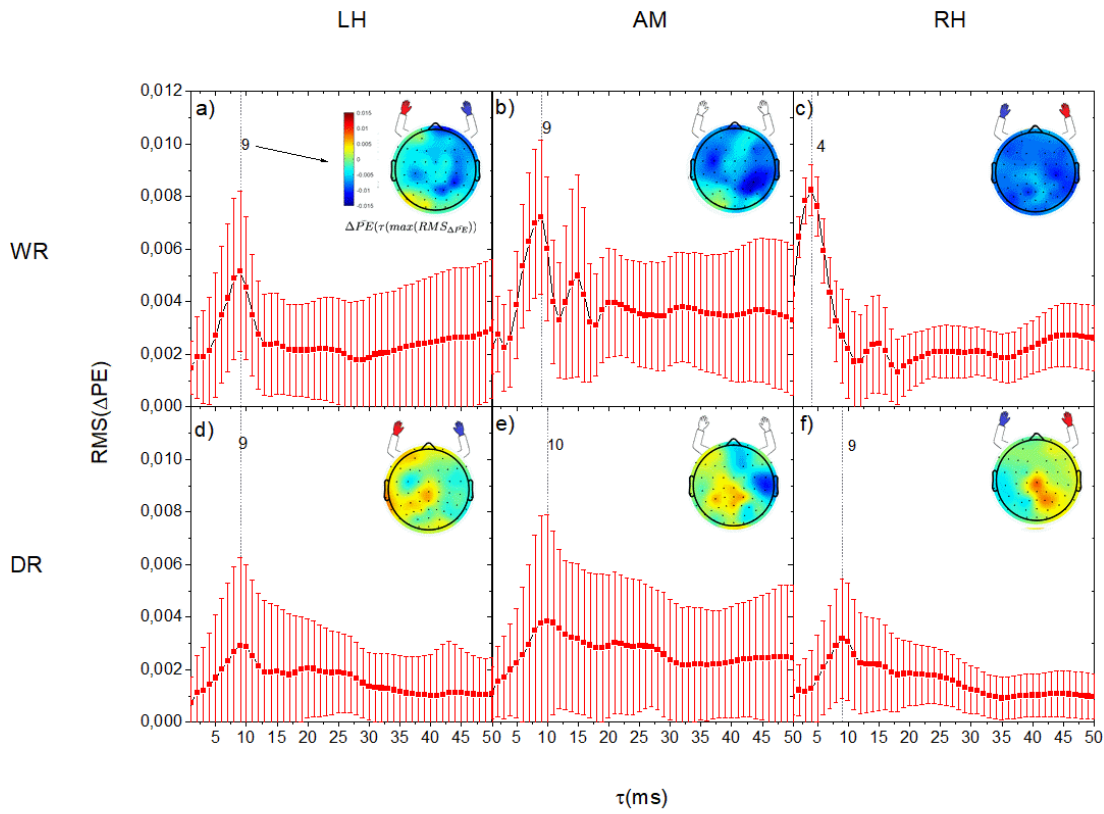


Figure 8.4: $RMS_{\overline{\Delta PE}}$ in function of τ . Brain maps of ΔPE of the τ associated to the respective higher $RMS_{\overline{\Delta PE}}$ are plotted as well. To facilitate comparisons, the dominant hand of the subject is in red and the non-dominant hand is in blue; WR: writing, DR: drawing; LH: left-handed; AM: ambidextrous; RH: right-handed.

Comparing across τ values we found interesting patterns when ordering electrodes by higher value of ΔPE (Figure 8.5). Left-handers and ambidextrous showed higher ΔPE values with $\tau = 9$ ms, mainly in right parietal electrodes: P2, CP4, CP6, highlighting the contralateral behavior of motor activity related with stability according to Hülsmüller et al., (2015); Milner et al.,

(2006); Reichenbach et al. and (2016). Right-handers in contrast, showed higher ΔPE values with $\tau = 4\text{ms}$, mainly in C4 electrode, well known as the main electrode related to left-hand motor activity (Brunoni et al., 2012, Silva et al., 2021). Moreover, right-handers had also higher values of ΔPE in their contralateral parietal area, left parietal with the electrodes P1 and P5, but a right parietal electrode as well (CP6) and others electrodes from temporal (T8) and frontal regions (F5, F6), (see Figure 8.5). Right-handers showed no spatial consistency between electrodes with the same regions (e.g. CP4 and CP6, P06 and P04, F5 and F7 are pairs of electrodes spatially neighbors, but very distant in the order of electrodes in Figure 8.5). Suggesting that this dynamic shows a non-linear and non-localized behavior.

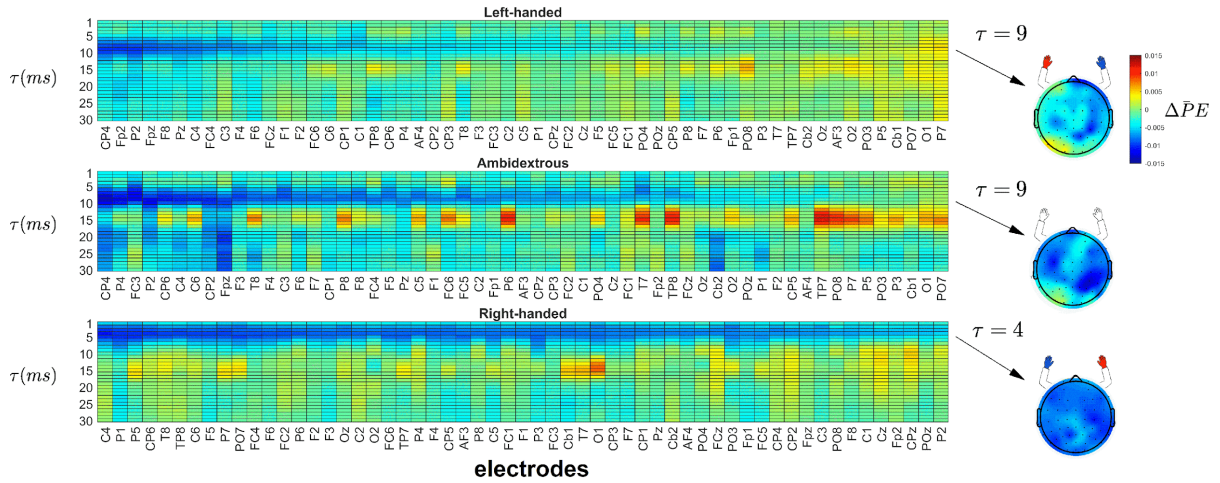


Figure 8.5: Heatmaps of the writing task EEG results of ΔPE values by τ and electrodes for mean values of left-handers, ambidextrous and right-handers, respectively. Electrodes are ordered by sorting ΔPE values of the τ associated to the main peak in Figure 8.4: 9ms for left-handers and ambidextrous and 4ms for right-handers.

Due to the proximity between $\tau = 9$ and $\tau = 10$ observed in ambidextrous participants during the drawing task, along with the high associated error bars, we focused our statistical analysis on $\tau = 4$ (right-handers during writing) and $\tau = 9$ (across other tasks). A three-way ANOVA (Task $\times$ Hand $\times$ Brain Region) was conducted to assess hand dependency in the EEG data at these two τ scales, which showed the highest lateralization in right-handers.

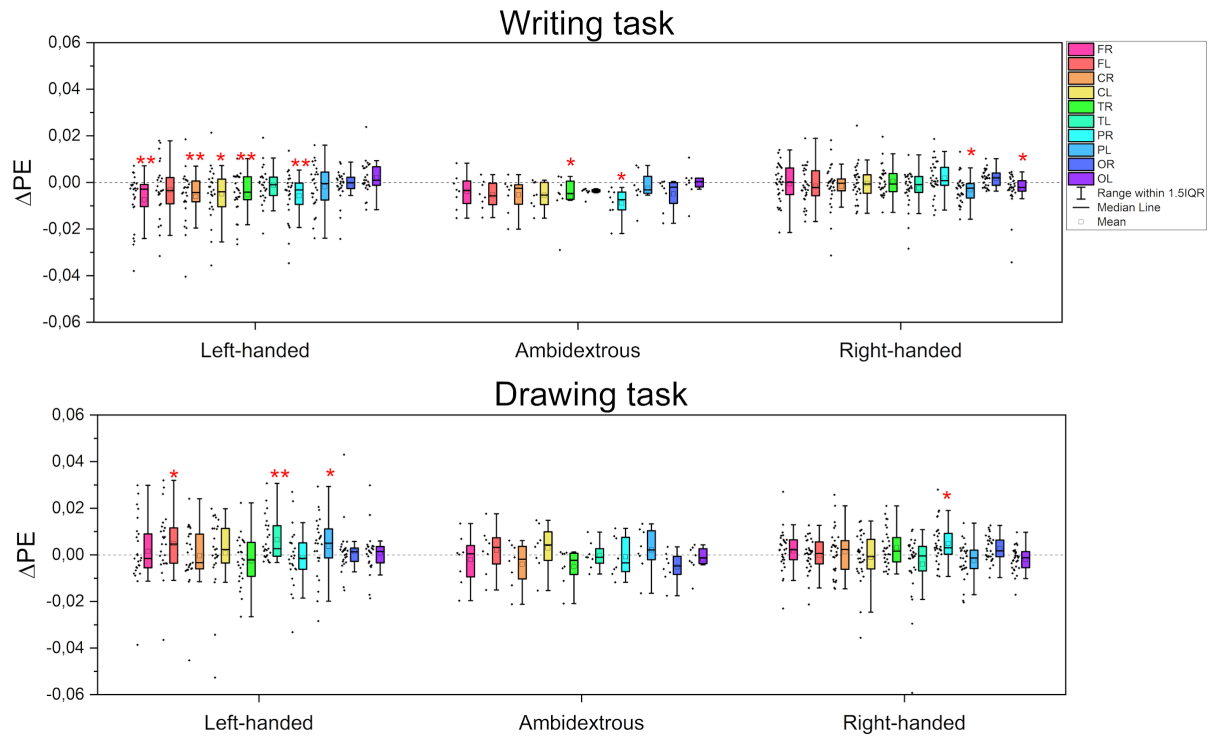
Although ΔPE values demonstrated strong lateralization in right-handers overall, the analysis revealed no statistically significant effects for $\tau = 4$ in right-handers. This suggests that the lateralization observed during right-handed writing is not specific to individual brain lobes but

rather reflects a more complex process involving nonlinear interactions among electrodes distributed across multiple regions. This interpretation is supported by Figure 8.4, where complex behavior is dominant during right-handers' writing. Notably, $\tau = 4$ falls in the middle of the observed power-law region, in contrast to $\tau = 9$, which lies just beyond this regime. Furthermore, as illustrated in Figure 8.5, several electrodes from distinct brain regions exhibit similar $|\Delta PE|$ values for right-handers, reinforcing the hypothesis of a nonlinear and spatially distributed pattern of brain activity during writing.

Using $\tau=9$ we found no significant difference in overall brain metrics when comparing hands ($F= 1.082$, $p=0.303$). However, analyzing post hoc comparisons by region revealed significant differences comparing hands: During the writing task we found differences in FR ($\Delta PE = -0.008$, $p<0.001$), CR ($\Delta PE = -0.006$, $p=0.005$), CL ($\Delta PE = -0.005$, $p=0.016$), TR ($\Delta PE = -0.004$, $p=0.008$) and PR ($\Delta PE = -0.005$, $p=0.005$) in left-handers; TR ($\Delta PE = -0.006$, $p=0.033$) and PR ($\Delta PE = -0.008$, $p=0.013$) in ambidextrous; PL ($\Delta PE = -0.003$, $p<0.028$) and LO ($\Delta PE = -0.003$, $p<0.022$) in right-handers.

Regarding the drawing task, we found significant differences in the regions: FL ($\Delta PE = 0.005$, $p=0.039$), TL ($\Delta PE = 0.007$, $p=0.005$) and PL ($\Delta PE = 0.004$, $p=0.034$) in left-handers; no significant difference in ambidextrous; RP ($\Delta PE = 0.005$, $p=0.013$) in right-handers. (See Figure 8.6).

For both left- and right-handers, we observed significant differences in the contralateral parietal lobe during the writing task, extending the findings of Ehrsson et al. (2000) to left-handed individuals. In contrast, the drawing task revealed significant differences in the ipsilateral parietal lobe, aligning with and expanding upon the results of Mihov et al. (2010) for left-handers. Although less pronounced, ambidextrous individuals exhibited a pattern similar to left-handers during writing, but showed no significant lateralized behavior during drawing. ΔPE significant values appoint a higher PE in non-dominant hand for writing task and lower values in non-dominant hand for drawing task.



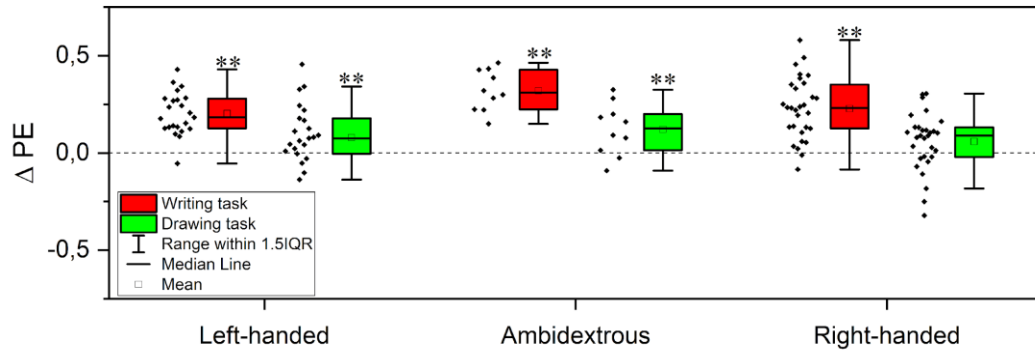
*($p < 0.05$), **($p < 0.01$)

Figure 8.6: Boxplot across regions of ΔPE for $\tau=9$.

Statistical results indicate that left-handers have more motor lateralization under ordinary dynamics (higher PE values, due $\tau > 8$) in both motor (central) and stabilization (parietal) regions, which represent simple behavioral changes, unlike previous studies appointing lower lateralization.

8.7. Biomechanical results

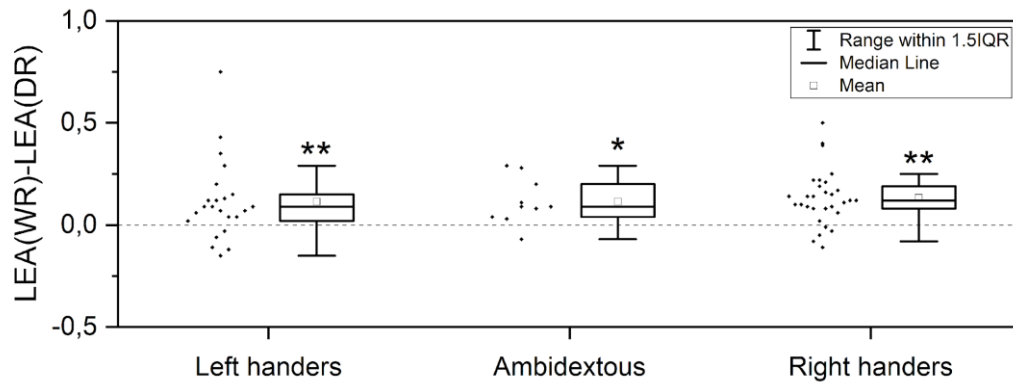
We did a two-way ANOVA (Task x hand) to compare PE in α time series in which significant differences were found comparing hands in all handedness groups and tasks ($F=79.107$, $p > 0.001$). Post hoc analysis reveal significant differences in left handers during writing task ($\Delta PE = 0.209$, $p < 0.001$) and drawing task ($\Delta PE = 0.075$, $p = 0.031$); in ambidextrous: writing task ($\Delta PE = 0.324$, $p < 0.001$) and drawing task ($\Delta PE = 0.134$, $p = 0.021$); right handers in contrast showed significance only in writing task ($\Delta PE = 0.214$, $p < 0.001$). (See Figure 8.7).



**($p < 0.01$)

Figure 8.7: ΔPE values for α time series.

Using the LEA index, we found that the writing process is more lateralized than drawing, being a more hand-dependent task. We did an ANOVA test comparing writing and drawing asymmetries, showing that in all groups, writing have higher values of LEA: Left-handers (mean difference=0.115, $p < 0.001$); ambidextrous (mean difference=0.117, $p < 0.022$), and right-handers (mean difference=0.132, $p < 0.001$). (See Figure 8.8).



*($p < 0.05$), **($p < 0.01$)

Figure 8.8: Difference between LEA writing and drawing index of α time series.

8.8. Discussion

This study successfully applied a framework from non-linear dynamics and information theory to investigate asymmetries in a complex biological motor system. Our approach's novelty lies in using permutation entropy (PE) to quantify the dynamics of the α exponent, a key parameter

from the motor control model proposed by Miranda et al. (2018). By linking these biomechanical dynamics to the complex characterization of concurrent EEG signals, we offer a new, quantitative lens through which to view motor control.

Neural Complexity Levels and Laterality: A bias issue

Neural analysis results shows that right-handers exhibit a distinct pattern of lateralization compared to left-handers and ambidextrous individuals having higher differentiation between hands in a shorter time reaction, that is an indicator of less elaborative movement, and a more primitive reaction (Honeycutt et al., 2008; Skurvidas et al., 2012). While our metrics indicate a strong lateralization process during complex tasks involving right-handed writing, left-handers and ambidextrous participants displayed results more similar to those observed during the drawing task, a condition that lacks inherent motor precision demands and emphasizes creative process over accuracy. Notably, these similarities were more pronounced under scale values (τ) that present ordinary dynamic conditions, which were associated with higher entropy values. Extreme high entropy reflects more random and less structured system behavior, representing a lower level of complexity compared to the organized variability characteristic of complex motor behaviors (Stergiou & Decker, 2011; Hsu et al., 2017).

Given that left-handers and ambidextrous individuals tend to use their non-dominant hand more frequently in daily life, the observed results may reflect differing levels of motor asymmetry. Specifically, complex dynamic patterns appear to emerge during unfamiliar, non-dominant hand use, highlighting the adaptive demands of such tasks. In contrast, ordinary or more random fluctuations may arise from inherent differences in stability and control, contributing to regions of pronounced lateralized behavior. Writing is not a task commonly performed with the non-dominant hand in daily life, given its complexity. This contrasts with simpler motor tasks examined in many studies (Yetkin et al., 2012; Lajtos, Barradas-Chacón, & Wriessnegger, 2023), which have characterized right-handers as a more lateralized group, exhibiting more localized neural differences. Overall, these findings suggest that right-handers may not be inherently more lateralized, but rather less familiar or practiced with precise tasks involving the non-dominant hand, being characterized in a more primitive reaction during left hand use for accurate motor tasks.

Biomechanical Degrees of Freedom

Our central biomechanical finding is that the dominant hand exhibits significantly higher permutation entropy in α time series. This suggests that the dominant limb operates with more varied dynamics. This result provides quantitative support for the long-standing theoretical framework of motor control proposed by Bernstein (1967), which posits that skill acquisition involves learning to manage the body's abundant degrees of freedom. The higher entropy can be interpreted as a "freeing" of these degrees of freedom, allowing the system to explore a richer state space of motor solutions. This is consistent with empirical observations in motor learning studies, which show that expert performance is characterized by functional variability, not rigid repetition. Conversely, the lower PE in the non-dominant hand reflects a "freezing" of degrees of freedom, a strategy often observed in the early stages of skill acquisition or in less-than-optimal conditions, where the system constrains its dynamics to ensure stability. This aligns with the framework proposed by Stergiou & Decker (2011), who argue that optimal, healthy biological systems exhibit complex variability, whereas stereotypy and lower complexity can be markers of pathology or suboptimal performance.

Task-Dependent Asymmetry

Neural results suggest that the activation patterns observed in right-handers are not strictly linked to a specific hemisphere, but rather to the dominant motor controller. Significant values of average Δ PE indicate higher entropy in the non-dominant hand during writing, reflecting increased neural effort, and lower entropy in the non-dominant hand during drawing, suggesting reduced creative engagement. This supports the idea that writing with the non-dominant hand requires greater motor control, while drawing with the non-dominant hand may interfere with the creative process, effectively turning the task into a dual demand and limiting genuine creative expression found in the dominant hand execution.

The magnitude of LEA asymmetry index was strongly modulated by task: lateralization was greater during writing than during drawing, consistent with findings that practiced, automatic skills exhibit more pronounced interlimb differences than novel tasks, such as the creation of a drawing that is not previously defined (Krishnan et al., 2018). While prior studies have

characterized handwriting asymmetry through kinematic measures (Phillips et al., 1999), our work extends these results by quantifying the complexity of the underlying control strategy itself.

A Bridge Between Controller and Output: Handedness and Brain Lateralization

While biomechanical analysis (the output) reveals similar patterns of lateralization across groups, the underlying neural dynamics (the controller) show distinct differences between right-handers, left-handers, and ambidextrous individuals. Through the lens of complexity science, we can distinguish between biological neural adaptation and the habitual use of the non-dominant hand. In left-handers and ambidextrous individuals, neural responses tend to exhibit more linear and consistent patterns across electrodes, suggesting a stable and symmetric control strategy. In contrast, right-handers appear to rely more heavily on motor adaptation mechanisms when engaging the non-dominant hand, resulting in more complex and variable brain dynamics.

8.9. Conclusion

This study presented a novel methodological framework combining Permutation Entropy (PE) and non-linear dynamics to analyze motor asymmetry and brain lateralization across handedness groups. By applying PE to both biomechanical α -exponents and EEG time series, we quantified the randomness of motor output and neural control during fine motor tasks with both hands. The approach effectively captured task-dependent asymmetries and highlighted how system complexity varies with motor familiarity and control demands. By linking neural and motor levels through a unified complexity metric, this framework offers a sensitive tool for studying motor control and lateralization in both research and applied contexts.

Based on our findings, we can address the study's research hypothesis:

1. Systematic Motor Control Hypothesis: The highest permutation entropy values in the EEG measurements were predominantly observed during tasks performed with the non-dominant hand. This supports our hypothesis that less familiar tasks elicit less predictable neural behavior. In contrast, we also found that, due to reduced degrees of freedom, tasks performed

with the non-dominant hand exhibit lower entropy. These findings therefore validate the systematic motor control hypothesis.

2. Task-Constraint Hypothesis: Our results on brain asymmetry indicate that lateralization is greater during writing tasks compared to drawing tasks (see Figure 8.4). A similar pattern is observed in the LEA measure (see Figure 8.8), which shows that hand asymmetry during writing is significantly greater than during drawing across all groups. These findings suggest a direct relationship between the degree of motor freedom and the level of neuromotor asymmetry.

3. Controller-Output Hypothesis: Our method revealed that right-handers show shorter neural time reaction when comparing dominant and non-dominant hands in accurate task (writing), suggesting predominance of motor primitive behavior and prioritizing initial contact with left hand use features rather than biological lateralization. In contrast, left-handers and ambidextrous individuals exhibited more symmetric and consistent patterns, likely due to habitual non-dominant hand use.

8.10. References

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9. SUPPLEMENTARY MATERIAL 2

EEG additional results and discussion

Additional analyses of the secondary peaks in Figure 8.4 reveal that at larger temporal scales, there are components where ΔPE becomes positive, contradicting the general trend observed in the main peaks. In these cases, PE is higher for the dominant hand. Using the same reasoning applied to interpret the dominant peaks, this result may be understood as a delayed neural response pattern associated with the non-dominant hand. While in the main peaks the non-dominant hand required greater neural control, indicating increased effort or lower familiarity, at this temporal scale ($\tau = 15$), the opposite pattern emerges: the non-dominant hand demands less neural control. This suggests that this specific scale may reflect a typical temporal scale of neural response for the non-dominant hand, pointing to an alternative motor control strategy (see Figure 9.1).

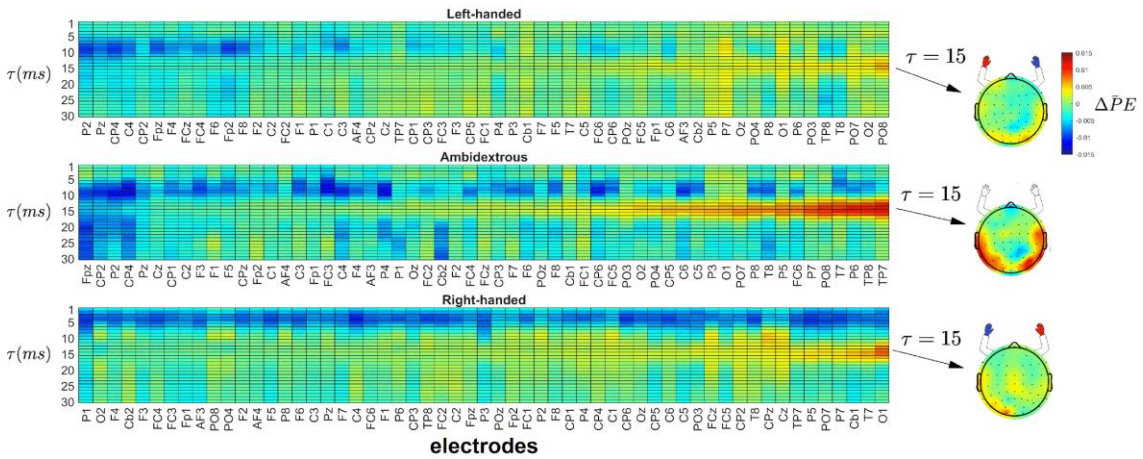


Figure 9.1: Heatmaps of the writing task EEG results of ΔPE values by τ and electrodes for mean values of left-handers, ambidextrous and right-handers, respectively. Electrodes are ordered by sorting ΔPE values of the τ associated to the secondary peak in Figure 8.4.

In Figure 9.1, we observe that the ambidextrous group shows a higher intensity of neural response when using the non-dominant hand, an expected pattern for individuals characterized by reduced manual preference. The highest Delta PE values are primarily localized in the temporal and occipital regions of both hemispheres. These areas are strongly associated with memory processes (Squire, 2004) and visual feedback processing (Milner & Goodale, 2006), both of which are crucial during handwriting tasks performed with the non-dominant hand. The

activation of these regions suggests a greater reliance on visuomnemonic strategies to compensate for the lower motor automatization typically seen in the non-preferred hand (Goble & Brown, 2008).

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10. CONCLUSION

A first characterization of the α parameter reveals that, across tasks, the difference between dominant and non-dominant hand performance is statistically significant only among right-handed individuals when writing. Since α is a metric derived from nearly 1,000 elements, it is mathematically feasible to compute it over smaller time windows, an approach adopted in **PAPER 2**. Results show that α is not a static measure; its patterns shift over time, particularly in the dominant hand, across all handedness groups, including ambidextrous participants. This finding suggests that α is inherently time-dependent and reflects the degree of motor freedom required by the task.

The same principle applies to EEG data: many static behaviors did not show significant differences in ERD/S analyses, yet meaningful neural distinctions emerged when the signals were segmented. Notably, ambidextrous individuals also exhibited lateralized neural behavior, often aligning more closely with left-handed participants. Interestingly, right-handers frequently showed significant differences even in broad motor behaviors, indicating more behavioral consistency, but this consistency should not be confused with greater lateralization per se.

Based on these findings, we can address the study's research questions:

1. Are left-handed / ambidextrous individuals more or less optimized in neuromotor measurements compared to right-handed individuals?

Our analyses suggest that neuromotor behavior depends fundamentally on training and experience with the non-dominant hand. In **PAPER 1**, we found that the W parameter—associated with motor expertise—was optimized by prior experience. In **PAPER 2**, we observed that the only group lacking localized neural behavior was right-handers, who, socially, use their non-dominant hand less frequently. Statistical results showed clear patterns of lateralization in both left-handers and ambidextrous individuals. Thus, the motor optimization observed in simple tasks appears to be a result of familiarity rather than intrinsic handedness traits.

2. What are the underlying factors that lead humans to develop a preferred hand?

Our results indicate that consistent practice shapes neuromotor development. Selecting one hand for specialized use results in greater exposure to motor training, which enhances its performance. This specialization offers evolutionary advantages to individuals with broader and more refined motor repertoire.

3. Do social and cultural factors influence hand preference and hand-dependent motor behavior?

Motor tasks are lateralized across all handedness groups; however, right-handed individuals exhibit a more pronounced pattern, as presented by PAPER1, right-handed individuals exhibit significantly lower cognitive load during the writing task with the dominant hand compared to all other tasks measured, particularly in the left- central and temporal lobes. This suggests a higher degree of motor familiarity with this specific task combining regions related to motor and memory activity. In contrast, when compared to writing with the non-dominant hand in PAPER 2, analysis reveal that the short response time is associated with more primitive and coarse motor response patterns, reflecting reduced familiarity with motor activity using their non-dominant hand, as indicated in PAPER 2. This suggests that the type of lateralization observed in right-handers is linked to their lack of experience using the non-dominant hand, an influence that is largely social. Therefore, social factors play a role in shaping the hand-dependent nature of motor behavior. Therefore, neuromotor lateralization is essential for the specialization of both left-handed and right-handed *Homo sapiens*. Individuals, with ambidextrous being a very small part of the population, and even then, they also have lateralized motor behavior.

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12. FUTURE DIRECTIONS: INTEGRATION OF TIME-VARIANT GRAPH ANALYSIS

While the present study has advanced the understanding of neuromotor behavior and lateralization through both biomechanical and EEG-based analyses, a key limitation of the current approach lies in its reliance on aggregated or static representations of neural and motor performance. This limitation restricts our ability to detect transient or state-dependent patterns that may emerge during task execution, particularly in complex behaviors like writing or hand alternation. To overcome this, we propose the implementation of Time-Variant Graph (TVG) analysis as a natural and robust extension of our current methodology.

TVGs offer a formal framework for modeling evolving relationships between elements in a network. In EEG research, this means capturing the dynamic nature of brain connectivity over time, rather than averaging connectivity across entire tasks or epochs. As established by Casteigts et al. (2012), TVGs incorporate not only the presence of nodes and edges but also the temporal dimension through a presence function, allowing researchers to map when and how neural interactions occur.

Given that our EEG recordings were structured around motor tasks with defined phases (e.g., initiation, execution, stabilization), a TVG framework would allow us to identify phase-specific reconfigurations in functional brain networks. This is especially relevant to our finding that the α parameter and EEG signals behavior varied significantly depending on time windows, handedness, and task conditions. Static connectivity metrics could not capture such nuances.

Applying TVG analysis would allow us to:

1. Detect transient patterns in functional connectivity that are otherwise obscured in traditional time-averaged analyses.
2. Compare connectivity reconfiguration across handedness groups (e.g., left-handed, right-handed, and ambidextrous individuals) and across dominant vs. non-dominant hand use.

3. Quantify network dynamics using time-resolved metrics such as dynamic centrality, graph entropy, and modularity (Bassett et al., 2011; Holme & Saramäki, 2012).
4. Investigate whether brain network flexibility or stability is associated with motor performance, effort, or lateralization strength.

In practical terms, TVGs could be constructed using a sliding-window approach on the EEG time series, extracting connectivity matrices at regular intervals and interpreting each matrix as a temporal "snapshot" of the brain network (Fraschini et al., 2016). These snapshots would then be compiled into a time-ordered sequence of graphs, enabling both longitudinal and comparative analysis.

Furthermore, TVG-based metrics like the E-Index (proposed in the current document) could be refined to quantify the proportion of intra- versus inter-regional connectivity over time. Such an index could help reveal whether motor control under non-dominant hand use engages more distributed (inter-regional) networks—suggesting compensatory mechanisms—or remains locally constrained.

Ultimately, the adoption of TVG analysis aligns with a broader shift in neuroscience toward non-stationary and multiscale models of brain function. In the context of handedness and motor lateralization, it opens new avenues to understand how the brain flexibly adapts to different motor demands, how this differs across handedness profiles, and how such adaptability might relate to developmental or rehabilitative outcomes. The example in Figure 8.2 highlight transitional behaviors when changing hands during writing

Preliminary results are displayed in Figure 12.1

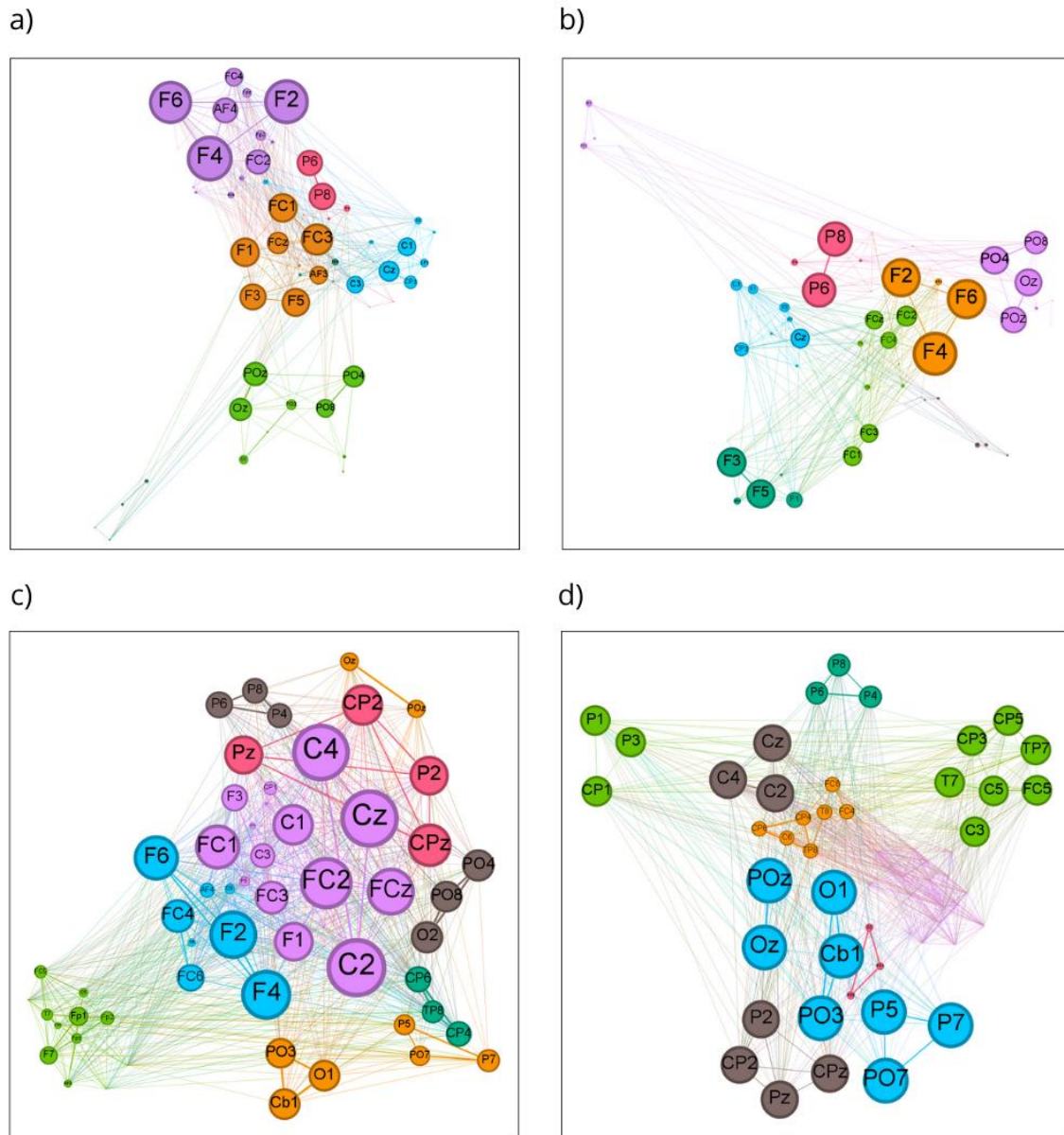


Figure 12.1: Network of connections between electrodes during writing task: a) Left-handed subject using dominant hand; b) Left-handed subject using non-dominant hand; c) Right-handed subject using dominant hand; d) Right-handed subject using non-dominant hand.

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13.APPENDIX 1: INFORMED CONSENT FORM (ICF)

**UNIVERSIDADE FEDERAL DA BAHIA
INSTITUTO DE FÍSICA - IF
ESCOLA DE DANÇA**

TERMO DE CONSENTIMENTO LIVRE E ESCLARECIDO (TCLE)

Título do estudo: “Relações entre a estratégia motora e a assimetria do movimento das mãos em indivíduos adultos saudáveis”.

Pesquisadores Responsáveis: José Garcia Vivas Miranda, Yago Emanuel Silva Ramos, Mariana Teixeira Santos e Cecília Bastos da Costa Accioly.

Destinado a: Participantes que atendem aos critérios de inclusão na pesquisa.

O(A) Senhor(a) está sendo convidado(a) como voluntário(a) a participar da pesquisa com título: **“Relações entre a estratégia motora e a assimetria do movimento das mãos em indivíduos adultos saudáveis”**. Por favor, leia este documento com bastante atenção antes de assiná-lo. Caso haja alguma palavra ou frase que o(a) senhor(a) tenha dúvidas ou não consiga entender, converse com o pesquisador responsável pelo estudo ou com um membro da equipe desta pesquisa para compreensão completa. A proposta deste termo de consentimento livre e esclarecido (TCLE) é explicar tudo sobre o estudo e solicitar a sua permissão para participar do mesmo.

Nessa pesquisa pretendemos descrever o comportamento neurológico e biomecânico das estratégias motoras (se refere ao seu movimento enquanto o(a) senhor(a) está escrevendo e desenhando) dos membros superiores, por meio da digitalização da trajetória da mão através do equipamento Motion Capture - MOCAP e verificação de atividade cerebral através do equipamento de Eletroencefalograma - EEG. Apesar de utilizar câmeras, nenhuma imagem sua é captada pelos equipamentos, apenas os movimentos das mãos e as ondas cerebrais são

registrados, sendo garantida a preservação da sua imagem. Além disso, descrever as características relacionadas a sua profissão, idade e dados relacionados a sua frequência em desenhar servirão para caracterizar o grupo de voluntários desta pesquisa, garantindo o sigilo de sua identidade.

O motivo que nos leva a realizar essa pesquisa é o fato de que desde o momento em que nossos primeiros ancestrais lançaram objetos para se proteger, o ser humano se inquietou para entender o movimento do corpo para lançar algum item e o movimento desses objetos por eles lançados. Por uma perspectiva mais recente, a biomecânica (e também aspectos da neurociência) foi criada para compreender o movimento humano em suas atividades. Então, nosso objetivo é analisar o movimento por uma perspectiva de mão dominante e mão não dominante, e compará-los com os padrões cerebrais.

Você foi escolhido(a) para participar do estudo porque tem idade superior a 18 anos, não utiliza equipamento no corpo para ajudar no movimento e não apresenta problemas para realizar a movimentação da mão.

A duração do estudo será de um ano, porém a sua participação no estudo será em apenas uma avaliação, sendo necessário apenas um encontro.

Após entender e concordar em participar da pesquisa o senhor(a) será levado(a) até uma sala onde os seguintes procedimentos serão explicados e realizados:

1. Será realizada uma avaliação inicial sobre suas informações gerais incluindo: nome, idade, profissão e frequência em que desenha. Um teste de avaliação de lateralidade manual será aplicado para avaliar a dominância das mãos.
2. Será colocada a touca de EEG sobre sua cabeça, aplicando-se um gel condutor hipoalergênico entre ela e seu couro cabeludo para intensificar os sinais eletroencefalográficos pelo equipamento, e a coleta dos dados ser realizada de forma eficaz. A touca permanecerá em sua cabeça durante todas as etapas.
3. Será a coleta de atividade basal - de olhos fechados, o(a) senhor(a) permanecerá sentado(a) com os antebraços sobre a mesa, durante o período de 120 segundos para termos um parâmetro

inicial de sua atividade cerebral. Em seguida, será realizada uma avaliação do seu movimento das mãos por meio do MOCAP. Serão registradas informações sobre duração, trajetória, velocidade e aceleração capturadas pelo movimento das suas mãos que informam sobre a estratégia motora. O(A) senhor(a) será devidamente orientado(a), será solicitado que retire acessórios que possam prejudicar a avaliação (relógios, pulseiras, anéis, pertences pessoais) e que possam alterar o movimento das mãos.

4. Será realizada a captura das imagens apenas das suas mãos, tanto da mão direita, quanto da mão esquerda, uma de cada vez, com intervalo mínimo entre elas, em três etapas: escrita, desenho livre e desenho guiado pela impressão que será disponibilizada logo antes da avaliação. Entre cada etapa, o(a) senhor(a) terá 2 (dois) minutos de descanso. Em cada etapa: será solicitado que o (a) senhor (a) se sente sobre uma cadeira e coloque seus antebraços sobre a mesa a frente, segure o lápis com a mão escolhida. Para a escrita, o tempo é livre e o(a) senhor(a) precisará preencher todas as três linhas por completo e de forma continuada entre as linhas, com a palavra “bahia” com letra cursiva. Para o desenho a mão livre, o(a) senhor(a) terá 2 min para desenhar algo de sua preferência de modo que dure o tempo limite. Para o desenho guiado, o tempo é livre e o(a) senhor(a) precisará cobrir cada uma das figuras desenhadas (elipses) três vezes e todas de forma continuada.

RISCOS POTENCIAIS, EFEITOS COLATERAIS E DESCONFORTOS:

Os riscos relacionados ao manuseio de equipamentos, bem como ao processo de desenho e escrita, serão minimizados durante a pesquisa, pois serão conduzidos por pessoas capacitadas. Também será concedido tempo de descanso entre as etapas para evitar desconforto para os participantes. Além disso, os riscos de vazamento de dados e perda de confidencialidade serão minimizados por meio da codificação dos dados dos participantes.

BENEFÍCIOS:

A pessoa participante levará como benefício uma avaliação de lateralidade, indicando suas proficiências em cada membro superior, além da relação das suas áreas do cérebro mais atividades para cada atividade proposta.

COMPENSAÇÃO:

Para participar do estudo, o(a) senhor(a) não terá nenhum custo e nem receberá nenhuma vantagem financeira. Nos casos de necessidade de gastos com deslocamento e alimentação para a realização da pesquisa, conforme direito do participante, este terá o devido ressarcimento.

PARTICIPAÇÃO VOLUNTÁRIA/DESISTÊNCIA DO ESTUDO:

Sua participação neste estudo é totalmente voluntária, ou seja, o(a) senhor(a) somente participa se quiser. Após assinar o consentimento, terá total liberdade de retirá-lo a qualquer momento e deixar de participar do estudo se assim o desejar.

NOVAS INFORMAÇÕES:

Quaisquer novas informações que possam afetar a sua segurança ou influenciar na decisão de continuar a participação no estudo serão fornecidas ao senhor (a) por escrito. Se o(a) senhor(a) decidir continuar nesse estudo terá que assinar um novo (revisado) Termo de Consentimento informado para documentar seu conhecimento sobre novas informações.

EM CASO DE DANOS RELACIONADOS À PESQUISA:

Em caso de dano pessoal, diretamente causado pelos procedimentos propostos neste estudo, o(a) participante tem direito às indenizações legalmente estabelecidas.

Todas as informações colhidas e os resultados dos testes serão analisados em caráter estritamente científico, mantendo-se a confidencialidade (segredo) do(a) participante a todo o momento, ou seja, em nenhum momento os dados que o(a) identifique serão divulgados, a menos que seja exigido por lei. Será realizada codificação dos dados de cada participante a fim de garantir confidencialidade.

Os resultados desta pesquisa poderão ser apresentados em reuniões ou publicações, contudo, sua identidade não será revelada nessas apresentações.

EM CASO DE DÚVIDA:

Em qualquer etapa do estudo você terá acesso aos profissionais responsáveis pela pesquisa para esclarecimento de eventuais dúvidas. Os pesquisadores responsáveis pelo estudo são José Garcia Vivas Miranda, Cecília Bastos da Costa Accioly, Yago Ramos, Mariana Teixeira e Norberto Peña que poderão ser encontrados no Instituto de Física, na Escola de Dança e no Instituto de Ciências da Saúde da Universidade Federal da Bahia.

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Como pesquisador, é importante entender e respeitar os direitos dos participantes em nossas pesquisas. Os participantes têm direito a um Registro de Consentimento Livre e Esclarecido, que deve incluir informações claras e acessíveis sobre a pesquisa, como sua justificativa, objetivos e procedimentos, bem como informações sobre possíveis danos e como eles serão evitados. Os participantes têm a liberdade de decidir se desejam participar ou não, e podem retirar seu consentimento a qualquer momento, sem prejuízo algum. Também é importante manter a privacidade e o sigilo dos participantes durante todas as fases da pesquisa, exceto quando houver sua manifestação explícita em sentido contrário. Além disso, os participantes têm direito a acesso aos resultados da pesquisa e a assistência durante a pesquisa. É necessário também informar aos participantes sobre o ressarcimento de despesas e o contato dos responsáveis pela pesquisa, bem como sobre o Comitê de Ética em Pesquisa e o registro do consentimento

DECLARAÇÃO DE CONSENTIMENTO:

Concordo em participar do estudo intitulado **“Relações entre a estratégia motora e a assimetria do movimento das mãos em indivíduos adultos saudáveis”**.

Li e entendi o documento de consentimento e o objetivo do estudo, bem como seus possíveis benefícios e riscos. Tive oportunidade de perguntar sobre o estudo e todas as minhas dúvidas foram esclarecidas. Entendo que estou livre para decidir não participar desta pesquisa. Entendo que ao assinar este documento, não estou abdicando de nenhum de meus direitos legais.

Todas as páginas do TCLE serão rubricadas, e assinadas ao final, pelo participante e pelo pesquisador responsável.

Eu autorizo a utilização dos meus dados obtidos na avaliação pelo pesquisador, autoridades regulatórias e pelo Comitê de ética em Pesquisa (CEP) da instituição. Esse documento foi emitido em duas cópias, sendo que uma delas será assinada por mim e pelos pesquisadores responsáveis e ficará em minhas mãos.

Salvador-BA, ____ de _____ de ____

Nome completo do participante	Data
-------------------------------	------

Nome completo do pesquisador responsável	Data
--	------

Nome completo da testemunha	Data
-----------------------------	------

José Garcia Vivas Miranda / Yago Emanuel Silva Ramos / Mariana Teixeira Santos / Cecília Bastos da Costa Accioly

O Comitê de Ética em Pesquisa é uma instância fundamental para a garantia da integridade ética na condução de pesquisas envolvendo seres humanos ou animais. O principal objetivo desse comitê é proteger os participantes da pesquisa, bem como a comunidade científica e a sociedade em geral. Para isso, o comitê é composto por um grupo de especialistas de diversas áreas do conhecimento, que avaliam os projetos de pesquisa, verificando se eles estão em conformidade com as normas éticas e legais estabelecidas. Além disso, o comitê também é responsável por monitorar a condução da pesquisa, a fim de garantir que as condições éticas estabelecidas sejam mantidas ao longo de todo o processo. O comitê de ética responsável por supervisionar essa pesquisa é o comitê de ética da Faculdade de Enfermagem da UFBA.

Em caso de dúvida: Entrar em contato com o CEP (cepee.ufba@ufba.br) para orientações, caso existam dúvidas. - Contatar o Comitê de Ética da Escola de Enfermagem da UFBA, via endereço Rua Augusto Viana S/N, 4º andar, sala 432-437, Campus do Canela, Salvador, Bahia, 40110- 060, telefone (71) 3283-7615 e/ou e-mail cepee.ufba@ufba.br. Atendimento das 11 às 15h.

Telefone: (71)3283-7615
Fax: (71)3263-7615
E-mail: cepee.ufba@ufba.br

14. APPENDIX 2: MINI-MENTAL STATE EXAMINATION (MMSE)

1. Como você avalia a sua memória atualmente?

(1) muito boa (2) boa (3) regular (4) ruim (5) péssima (6) não sabe

Total de pontos _____

2. Comparando a um ano atrás, o você diria que sua memória está?

(1) melhor (2) igual (3) pior (4) não sabe

Total de pontos _____

ORIENTAÇÃO TEMPORAL:

Anote um ponto para cada resposta certa.

3. Por favor, diga-me:

(1) Dia da semana (2) Dia do mês (3) mês (4) ano (5) hora aproximada

Total de pontos _____

ORIENTAÇÃO ESPACIAL:

Anote um ponto para cada resposta certa.

4. Responda:

Em que local nós estamos? (consultório, hospital, residência) ()

Qual é o nome deste lugar? (hospital, cozinha) ()

Em que cidade estamos? ()

Em que estado estamos? ()

Em que país estamos? ()

Total de pontos _____

REGISTRO DE MEMÓRIA IMEDIATA

5. Eu vou dizer três palavras e você irá repeti-las a seguir, preste atenção, pois depois você terá que repeti-las novamente. (dê 1 ponto para cada palavra) Use palavras não relacionadas.
(Árvore, mesa, cachorro)

() A () M () C

Total de pontos _____

ATENÇÃO E CÁLCULO:

6. Vou lhe dizer alguns números e gostaria que realizasse alguns cálculos:

100-7: _____, 93-7: _____, 86-7: _____, 79-7: _____, 72-7: _____

(93, 86, 79, 72, 65)

Total de pontos _____

MEMÓRIA RECENTE:

7. Há alguns minutos, o (a) senhor (a) repetiu uma série de três palavras. Por favor, diga-me agora quais ainda se lembra.

() A () M () C

Total de pontos _____

Anote um ponto para cada resposta correta.

LINGUAGEM:

Anote um ponto para cada resposta correta.

8. Aponte a caneta e o relógio e peça para nomeá-los

() C () R

Permita 10 segundos para cada um

Total de pontos _____

9. Repita a frase que vou lhe dizer (repetir em voz alta, bem articulada e lentamente).

“Nem aqui, nem ali, nem lá”.

Total de pontos _____

10. Dê ao entrevistado uma folha de papel, na qual esteja escrito em letras grandes: **FECHE OS OLHOS**: Leia este papel e diga o que está escrito.

Permita 10 segundos.

Total de pontos ____

11. Vou lhe entregar um papel e quando eu te entregar, pegue com a mão direita, dobre-o na metade com duas mãos e coloque-o no chão.

() P () D () C

Total de pontos ____

12. Pedir ao entrevistado que escreva uma frase em um papel em branco.

O senhor poderia escrever uma frase completa de sua escolha? (contar um ponto se frase tiver sujeito, verbo, predicado sem levar em conta erros de ortografia ou sintaxe). Se o entrevistado não fizer corretamente, pergunte-lhe: Isso é uma frase e o permitir corrigir se tiver consciência do seu erro (máximo de 30 segundos).

Total de pontos ____

13. Por favor, copie este desenho (entregue ao entrevistado o desenho e peça-o para copiar). A ação está correta se o desenho tiver dois pentágonos com intercessão de um ângulo.

Anote 1 ponto se o desenho estiver correto.

Total de pontos ____

ESCORE TOTAL _____ (até 30 pontos)

15.APPENDIX 3: EDINBURGH HANDEDNESS INVENTORY (EHI)

HANDEDNESS / Lateralidade (Edinburg Handedness Inventory)

Data: _____

Nome: _____

Favor indicar com que mão você prefere fazer cada uma das atividades abaixo listadas, marcando (+) na coluna apropriada. Se a preferência é tão forte que você só utilizará a outra mão se for absolutamente forçado, marque (++). Se você utiliza qualquer uma das mãos, indistintamente, marque (+) em cada coluna. Responda a cada questão.

	Esquerda (E)	Direita (D)
Escrever		
Desenhar		
Costurar (mão que segura a agulha)		
Segurar um par de tesouras		
Escovar os dentes		
Segurar uma faca		
Segurar uma colher		
Segurar uma vassoura (mão de cima)		
Acender um fósforo (mão que segura o fósforo)		
Abrir uma caixa (mão que segura a tampa)		

Favor deixar em branco linha abaixo

QL :	$(D-E)/(D+E)$	QL relativo:	$QL*100$
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16.EPILOGUE: FINAL CONSIDERATIONS AND NEW RESEARCH HORIZONS

The results highlighting the importance of manual repertoire and exposure to non-dominant hand use among left-handers, combined with their apparent aptitude for intraspecific conflict (i.e., with individuals of the same species or group), lead us to reflect on the potential evolutionary significance of this group. While the high development of fine motor skills—especially among right-handers—has conferred a range of advantages over other species, left-handers appear to hold a particular advantage when dealing with individuals of the same species.

This allows us to hypothesize that the *Homo* genus became specialized in fine motor tasks, but the presence of highly skilled and competitive left-handed individuals may have provided a key advantage in natural selection processes within the genus itself. This interplay could have contributed to the emergence of *Homo sapiens* as the dominant specie among other hominids.

The hypothesis of cooperative dynamics between right- and left-handers in human evolution will be further explored through evolutionary population modeling.