SENSORIMOTOR CHALLENGES IN DEVELOPMENTAL DISABILITIES: IMPLICATIONS FOR ASSISTIVE TECHNOLOGY AND AUGMENTATIVE ALTERNATIVE COMMUNICATION

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Abstract

The provision of physical support through touch is a frequent and often spontaneous component of daily practice among professionals in special education, rehabilitation, and Assistive Technology (AT). Over the past 30 years, however, the use of touch assistance in relation to developmental disabilities (DD) has often been linked with controversial approaches such as Facilitated Communication (FC), rapid prompting (RPM), or spelling2communicate (S2C). This thesis starts (Chapter 1) with a consideration of these methods, particularly facilitated communication, in the context of AT and Augmentative Alternative Communication (AAC), showing how research has mainly focused on evaluating the authorship of the textual outputs produced via such techniques, neglecting in large part the dynamic that leads to the generation of such outputs. Chapter 1's conclusion is a call for approaches to Facilitated Communication and similar techniques that investigate all the possible levels of user and facilitator contribution and address the mechanisms underlining the facilitation process. Accordingly, the thesis pursues two research interests: evaluating the value of existing touch-based assistive approaches (Chapter 2 and 3) and exploring the mechanism by which touch-based support can benefit users with developmental disabilities in (Chapter 4 and 5). Chapter 2 applies quantitative linguistics to the analysis of authorship style to corpora of FC text written over a 20-year period by multiple users working with multiple facilitators. This analysis shows that both users' and facilitators' stylistic fingerprints are detectable in text written with FC, and therefore an assistive method like it is best understood as a co-creative process. Chapter 3 presents an empirical investigation of the pointing gestures at the keyboard exhibited during FC. Using movement and eye-tracking analysis, this study shows that users' movement behaviour cannot be explained exclusively in terms of facilitator influence or cueing, and that they should be acknowledged of some degree of literacy skills. It also becomes clear that participating in FC is not always associated with linguistic participation in text generation for at least some users.

Chapter 4 presents a neurocognitive hypothesis of the pathway by why touch may assist users with DD by reducing the cognitive load of motor-postural control, freeing up capacity for higher order cognitive tasks such as text generation. Chapter 5 begins the empirical evaluation of this hypothesis using fNIRS to track the effect of touch on frontal brain activation. The results suggest that frontal brain activation can be modulated by the provision of touch support especially when the postural context of the task becomes more challenging, and that the effect of touch may have a different direction and magnitude in individuals with and without cognitive capacity limitation. The concluding Chapter 6 focuses on integrating the various lines of research addressed in the thesis. First, FC and FC-like techniques are presented in a renewed perspective, whereby the user's participation and literacy development, and not the prospects of autonomous communication, are considered the primary goals. Second, the facilitating role of touch support deserves further consideration in the context of DD, not only in relation to existing touch-based assistive techniques, but more importantly in relation to the development of new assistive and rehabilitation programs.

Declaration

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Chapters 2 and 4, as well as part of Chapter 6, have been reported in two published papers. Chapter 3 has been submitted for publication and is currently under editorial review. All of these works are the result of collaboration with the group supervising my PhD. The group's contribution to both the published work and the content presented in this thesis was limited to discussing the results and revising the writing. All the results presented in this thesis are based solely on the candidate's work conducted during his PhD.

Publications

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TABLE OF CONTENTS

FIGURES CONTENTS

TABLES CONTENTS

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CHAPTER 1: FACILITATED COMMUNICATION (FC) IN THE CONTEXT OF ASSISTIVE TECHNOLOGY (AT)

1.1 Introduction

In this opening chapter, we aim to explore Facilitated Communication (hereafter also referred to as FC) within the broader framework of Assistive Technology (AT). AT encompasses a range of strategies and devices designed to help individuals with disabilities perform tasks with a level of effectiveness that would otherwise be unattainable. We begin in section 1.2 by offering a thorough description and classification of Assistive Technology. A key feature of this chapter is the introduction of innovative methods for categorizing Assistive Technology. In addition to the traditional classifications based on application area and technological complexity, we propose a new categorization that considers the type of impairment the AT addresses—whether sensory, motor, or cognitive—and the intended purpose, distinguishing between rehabilitative use and lifelong assistance. This will provide a foundation for discussing FC—a technique that involves physical support to aid in typing (section 1.3). Here we present a definition of FC (section 1.3), its historical background (section 1.4) and we introduce the literature on it (section 1.5). FC emerged in the 1990s as one of several assistive techniques that evolved organically from practice before being formalized into structured approaches. However, over the years, these techniques, including FC, have not met the standards of Evidence-Based Practice and are therefore their use is not recommended but strongly discouraged (section 1.6).

This chapter lays the groundwork for our research project. In the final paragraphs (section 1.7), we will outline the project's objectives and provide an overview of the content covered in each subsequent chapter.

1.2 Assistive Technology (definition and classification)

Under the umbrella term of Assistive Technology, we usually refer to the set of methods, strategies and applications that allow a user to accomplish a task at a level they would not be able to perform otherwise. Within a narrower perspective, AT refers to the set of tools specifically designed or adapted to enable a person with a disability to overcome some limitations. As such, AT implies the application of a device external to the users specifically deputed to assist the accomplishment of a specific task.

One possible means of ATs classification regards the application domain: Wendt et al (2011) refers to eight areas that can benefit from the implementation of assistive tools:

- Augmentative Alternative Communication: AAC involves tools and strategies designed to enhance or replace traditional spoken communication. Examples include communication boards, speech-generating devices, and symbol-based systems, catering to individuals with communication impairments.

- Adapted Computer Access: This domain focuses on technologies that enable individuals with various abilities to access and interact with computers. It encompasses a range of tools such as eye-tracking systems, alternative keyboards, switches, and software adaptations for customized computer control.
- Hearing and Visual Impairment: Assistive tools for hearing impairment include hearing aids, cochlear implants, and captioning systems. For visual impairment, tools like screen readers, magnifiers, and Braille displays enhance access to information and communication.
- Adapted Play and Recreation: This area caters to tools and strategies that allow individuals with disabilities to participate in recreational activities. Adapted toys, games, and sports equipment, as well as inclusive design principles, fall under this category.
- Seating and Positioning: Assistive tools in this domain focus on optimizing posture and comfort for individuals with mobility or positioning challenges. Examples include customized wheelchairs, orthopaedic seating systems, and postural support devices.
- Mobility: Mobility-related ATs address the need for increased independence and accessibility in movement. This includes wheelchairs, scooters, walking aids, and devices for environmental navigation.
- Prosthetics: Prosthetic devices are designed to replace or augment missing or impaired body parts. This includes artificial limbs, hands, or other appendages, customized to restore functionality and mobility.
- Environmental Control: Tools in this domain enable individuals to control their surroundings. This includes smart home technologies, voice-activated systems, and environmental adaptations to enhance independence in daily activities.

AT can also be classified between low-tech and high-tech technology. The distinction between low-tech and high-tech is nuanced, fluid and often related to the cost of the tools (Wendt, 2011; Alzrayer, 2020; Al-Hendawi et al., 2023). The key distinction lies in the level of technological complexity and cost. Low-tech solutions are simpler, more affordable, and easier to use, while high-tech solutions involve advanced technologies and may provide more sophisticated features and customization options. As an example, in the case of an assistive tool for a picture-based communication system a low-tech solution would be represented by a paper-book with the different symbols displayed on and categorized. A high-tech solution would be represented by a tablet with a software dedicated to host a picture-based communication system (Beukelman and Mirenda, 2012).
The distinction between low-tech and high-tech mostly focus on the physical nature of the assistive support system, be it analogical or digital. However, in the aforementioned example, we could also consider the picture-based communication system as an assistive tool. Indeed, the picture-based system is a strategy specifically generated to overcome a linguistic limitation. This interpretation would expand the consideration of AT beyond the mere physical tool, stretching the boundaries of its meaning and therefore including the application of methodologies and interface systems within.

Another means of classifying ATs could relate to the nature of the impairment the AT is designed for. Broadly, AT can be designed for or adapted to overcome sensory, motor, and cognitive limitations. The distinction between limitations is not impermeable, thus tools can be designed to overcome simultaneously different limitations.

Some ATs created for sensory limitations are well-established in our collective consciousness, such as eyeglasses, magnifying glasses, or hearing aids (Wendt, 2011). These tools directly address sensory impairments and have become familiar symbols of assistance. Yet, within this category, the scope extends to include subtler but equally impactful technologies, such as video subtitles, automatic text readers, and walking sticks.

Expanding our perspective on technology to encompass any cultural byproduct, we can push the boundaries of AT categorization. This broader viewpoint incorporates not only tangible tools but also communication systems and languages. For instance, braille codes, sign languages, and tactile signing systems emerge as crucial assistive tools designed (in the case of braille or tactile signing) or naturally evolving (as seen in specific sign language systems) to overcome sensory limitations (Goldware and Silver, 1998; Sigafoos and Drasgow, 2001; Van Balkom and Verhoeven, 2010; Theil et al., 2020). In this specific context, languages or codes adopted for communication can also be considered as assistive tools within the field of Augmentative and Alternative Communication. Recognizing these linguistic and communicative tools as essential components of AT underscores the diverse range of strategies and technologies available to enhance accessibility and inclusion for individuals with sensory challenges.

Within the realm of ATs designed to address motor limitations, a broad spectrum of tools has been developed to enhance mobility, communication, and interaction with the external environment. Notable examples include wheelchairs, which not only provide mobility but also contribute to improved posture, and walking canes, essential for mobility while minimizing the risk of falling. The array of specific assistive tools is extensive, ranging from modified cutlery to movement sensors and adapted handles to prosthetics. These tools are tailored to support the individual needs, promoting independence and mitigating the impact of motor challenges on daily activities. Moreover, a pivotal category within this domain is accessibility tools. These encompass a diverse set of instruments enabling individuals to interact with computers and the broader digital environment despite motor limitations. Examples include eye-tracking systems, switches, joysticks, vocal control systems, sip and puff equipment, or brain-computer interfaces (Jeffs and Castellani, 2010; Päivi, 2011; Zickler et al., 2011; Hoppenbrouwers et al., 2014; Lupu et al., 2017; Grewal et al., 2018; Alzrayer, 2020; da Silva Junior and Germanovix, 2020; Edughele et al., 2022). These tools not only facilitate computer access but also empower users to control, navigate digital interfaces effectively. Additionally, software adaptations play a crucial role in this context, allowing systems to function seamlessly under modified controls and the user to actively interact with the system beyond their motor limitations to execute or accomplish a task (Lupu et al., 2017).

With regard to the ATs designed to overcome cognitive limitations we can count any system that simplify the interaction of the user with the world, be it by providing temporal or spatial cues, reminders in the case of memory difficulties, procedural cues in the accomplishment of complex tasks. Also, any simplified communication system may fall under this category. Let's return for example to the example of picture-based communication system (Beukelman and Mirenda, 2012). While it can be implemented also to overcome some oral-motor impairment (even temporary as with some intensive care patients) this system can provide a simplified access to communication, by removing or reducing the load of morpho-phonological computing, by providing a clearer relationship between the sign (picture) and its referent (the meaning), by facilitating the lexical and semantical retrieval. Similarly, to what described in the previous paragraph, the use of such system allows the user to access communicative content. To allow the user to interact with the environment through such method, the picture-based system should be organized and categorized in a way that can allow the user to orientate through the picture and respond to the environment requests. Remaining in the domain of communication, an everyday tool of cognitive simplification is represented by the word prediction system available in any virtual keyboard as those we commonly find in our smartphones. While the tools were designed to save us some typing time, in an assistive perspective it can easily be imagined as a tool that reduce the load of phonological and morphological computing as well as lexical retrieval. Even software may be designed to reduce the cognitive difficulty associated to a task. Let's thing for example to a video game that can adapt to the user's speed of processing, by adapting the time-pressure associated with the game or adapting to the executive functions' levels of the user. The same automatic text readers we presented in the context of sensory impairment can be implemented to favour and overcome reading difficulties due to for example to dyslexia and ease up textual comprehension. Within this framework, we can count software that provides simplification of the text difficult to comprehend (as some particular bureaucratic language can be) by using synonyms for uncommon words, by simplifying the syntactic structure, by reformulating (Sciumbata, 2021).

Another mean of ATs' classification could be that based on ATs intended purpose. In certain instances, AT devices or strategies are employed with a habilitative-rehabilitative perspective. The primary goal here is to facilitate skill development or rehabilitation, aiming for a gradual fading of the dependence on the assistive technology. The overarching objective is to empower users, fostering increased autonomy and self-sufficiency over time. Conversely, in different circumstances, AT solutions are designed to remain stable, serving as enduring support mechanisms. In these cases, the focus is on providing consistent and reliable assistance to individuals whose needs may not substantially change over time. The stability of such solutions ensures ongoing support, allowing users to integrate the AT seamlessly into their daily lives without the expectation of gradual independence from the technology.

1.3 Facilitated communication in the context of Assistive Technology

Facilitated Communication can be defined as an assistive technique that aims at increasing the communicative opportunities of people with different kinds of disabilities. The technique, in its classic application, involves a facilitator (a professional or a carer) and a user (Schlosser et al., 2014). The facilitator assists the user during a typing task by providing a touch based physical support. The facilitator may provide physical support at the level of the user's elbow, shoulder, wrist, hand, back, leg or neck. The level of facilitation changes between users and in some cases is idiosyncratic to the user-facilitator pair (Grayson, 1997). Within the same users it may happen that the level of facilitation modifies across time. Within this set-up, through the help of their facilitator, the user types using a keyboard or a letterboard, usually one key at a time. The linguistic output is then displayed on the PC's screen, if the user were using a keyboard or, if the user were using a letterboard, it can be spelled out by the facilitator (Jaswal et al., 2020). The FC-typed content may be part of a dialogic conversation, with the facilitator or with some external interlocutor, or rather be an independent textual output that could serve different purposes, from letters to poetry, from essays to narrative pieces. Notably, in the former case FC usage is in substitution of the oral language, in the latter, FC usage falls properly within the written language production. This double function of FC has allowed its application not only in the everyday life to meet conversational purposes (expressing needs or thoughts) but also in academic contexts as schools and universities.

The categorization of FC as a subfield of AT or AAC is disputed, for the only reason that FC has not received any significant scientific validation (Mostert, 2001; Wehrenfennig et al., 2008; NICE, 2012; Saloviita et al., 2014; Beals, 2022). In the following paragraphs, we will have the chance to further address the literature and the controversies on FC. For the time being, leaving aside any judgment or comment on the efficacy or validity of this intervention, we propose that FC can be considered an assistive tool at least in the purpose that leads its application. FC is an assistive strategy that aims at enhancing the communication opportunities of people with developmental disabilities (DD), through the provision of an externally provided physical support (Grayson, 1997). With a reference to the classification models of AT afore described, to the existing literature on FC, the technique could be defined as:

(a) an Augmentative Alternative Communication tool since it seeks to provide a modified access to communication

(b) a low-tech Assistive Technology, since it requires the use of simple keyboard and in some circumstances of a text editor

(c) an AT that mostly aims at overcoming motor limitations. FC earlier proponents suggested that the role of the facilitators' touch is mainly to facilitate the execution of the pointing task, reducing the perseveration of the gesture and enabling the initiation of the pointing gesture (Biklen, 1990)

(d) a lifelong assistive tool rather than a training/rehabilitative assistive tool since the literature does not acknowledge users that have started to type without the facilitator's physical assistance.

With respect to other assistive tools, the exception of FC resides in the fact that the assistance is not provided by a piece of inert technology but rather by a human being. Such human driven assistance is, as we will have the chance to see, the origin of the ongoing debate around FC and its applications.

1.4 History of Facilitated Communication

The FC technique that is used nowadays is the direct continuation of the work of Rosemary Crossley to whom we owe the name Facilitated Communication. Crossley developed the technique in the mid-seventies in Australia, firstly applying it with Anne McDonald, a user with cerebral palsy (Crossley, 1997). The technique was then exported to the US through the work and practice of Douglas Biklen, from there it starts diffusing across the world (Biklen, 1990). To this date, FC groups in Europe are counted in the UK, in Denmark, in Sweden, in France, in Germany and in Italy, but it is probable that FC also counts isolated users not affiliated to any FC group scattered around the world.

The development and diffusion and usage of FC is anticipated, parallelled and followed by the spurt of techniques that have a familiar resemblance to FC itself. Biklen (1990) dates the first example of a technique similar to FC back to the late sixties and in particular to the paper published by Edith and Thomas Goodwin (1969). There, they present the application of the Edison Response Environment (E.R.E) with children with Autism. In the paper they reported a surprising development of literacy skills on behalf of some users with autism, beyond what they would have expected. The scientific report described how some of the participants involved in the E.R.E project showed improvements in literacy skills in shorter periods of time.

The E.R.E equipment, also known as a the "talking typewriter", was a technological tool used to assist children in the development of literacy skills (reading and writing). Within the multiple functionalities of the typewriter, there was the possibility to reproduce the phonetic sound corresponding to the key pressed and of the word typed or the chance to lock the keyboard to a specific sequence of characters. This specific functionality was designed to allow children to explore the keyboard and train with spelling while reducing risks of committing mistakes. Since only the correct key could be depressed in the keyboard, the user could only type the correct sequence of characters and through that simultaneously learn the correct spelling.

It is worth noting that the connection acknowledged between the talking typewriter and FC looks mostly connected to the fact that both the approaches involve a keyboard and that the users showed at some point literacy skills beyond expectancy, as no external support was provided to users while using the talking typewriter.

Among other example of FC like techniques pre-FC, it is noteworthy the case of Rosalind Oppenheim (1961). Oppenheim developed a touch based assistive technique, hand over hand, that allowed users with autism to increase their performance with handwriting. In this scenario, the only difference between FC and the technique developed by Oppenheim resides in usage of pencils instead of keyboards. The touch-based assistive support and the observed increased users' literacy skills are semi-identical features of the two techniques.

In more recent years, other techniques who share with FC some familiar resemblance emerged. Some techniques as the Rapid Prompting Method (RPM) or Spelling to Communicate developed independently from FC (Schlosser et al., 2019). According to this method, users can type to a keyboard or a letterboard held by an assistant. While there is no touch-based assistance, RPM resemble FC in the use of keyboards or letterboard and in the fact that users exhibit unexpected literacy skills. Other techniques instead directly originated from FC and likewise implement touch-based support. These include the Written Output Communication Enhancement (W.O.C.E.) (Bernardi, 2008) or assisted/supported typing (Lilienfeld et al., 2014; Jaswal et al., 2020).

We should note that the common trait that brings together all these techniques is the emergency of unexpected competencies in the users that are exposed to these assistive methods. The perspective of unveiling some hidden competences was, and probably is nowadays, the driving force that favour the diffusion of FC and its application, especially in those circumstances where FC appeared as a last resort, in some cases, after years with few successes with other rehabilitative programs or assistive methods. Moreover, in apparent contrast to other AAC methods, FC and FC-like techniques grant users the access to a full language, enabling them to exploit the property of the human language and, in some cases, to express at high levels of written eloquence. Thus, the expectancy of extraordinary results in a relatively small amount of time was a key of the FC and FC-like success but also the core of the scientific debate that started in the nineties and continues to this day. In fact, if the principle 'extraordinary claims require extraordinary evidence' held true, the research and literature on FC have thus far fallen short in delivering such evidence.

1.5 Scientific literature on Facilitated Communication

The validity of the technique was contested multiple times in the last three decades (Lilienfeld et al., 2014). After some court cases where testimony had to be collected via FC (Jones, 1994), the technique was put under the lens of the scientific research. Controversies around the techniques were and still are due to concerns over the extent to which the facilitator contributes to the user's communication (Sbalchiero and Neresini, 2008). Research programs were set-up with the goal of ascertaining about the contribution of the user to the generation of communicative contents, thus to what extent the FC user was the author of the texts produced. In the case of FC, for example, where the facilitator assists the user's postural and motor stability by touching their shoulder or holding their arm, it has been suggested that the texts produced are simply by-products of the facilitators' unconscious cueing of the users' movements towards the keyboard.

A range of studies have attempted to address FC with different experimental methods. The prevailing task that has been adopted to evaluate Facilitated Communication is message passing. In this task, FC participants are asked to type information (often single words) their facilitator is either informed, uninformed, or misinformed. The experimental attempts with the message passing task have led to the conclusion that the user's output is in most cases strongly influenced by the facilitator. In fact, in most cases, FC users could pass information not known by their facilitators at a highly unsuccessful rate (Mostert, 2001; Wehrenfennig et al., 2008; Mostert, 2010; Saloviita et al., 2014; Schlosser et al., 2014), within a controlled experimental setting. With regards to passing information unknown to the facilitator, some research report anecdotical evidence of message passing outside experimental condition (Beals, 2024). In the wake of these results, Burgess (1998) suggested that supported typing techniques were an example of the ideomotor effect (Carpenter, 1875) and Wegner et al. (2003) compared them to the episode of Clever Hans, the horse that reportedly answered mathematical questions with its hoof by reading subtle cues coming from his breeder. The ideomotor effect has since become the only widely discussed and accepted theoretical explanation of what occurs in supported typing (Schlosser et al., 2014; Saloviita, 2018). According to this hypothesis, the output generated through the user-facilitator interaction, is the byproduct of facilitators' unconscious and subtle cueing of users' movements towards the keyboard. As such, FC users are antennas that sense users cueing and transform it into a written output. As a result, these techniques are currently not recommended as an assistive framework in formal education (NICE, 2012) although their practice has continued widely (Lilienfeld et al., 2014), and research on supported typing has persisted over the last two decades, with the adoption of different methodologies. Some researchers have used eye-tracking methods (Grayson et al., 2012; Jaswal et al., 2020) to show that users anticipatorily fixate the to-be-typed key, and so are actively involved in the process. Others have sought to assess and evaluate textual contents produced via such techniques adopting qualitative and quantitative linguistic analysis (Zanobini and Scopesi, 2001; Niemi and Kärnä-Lin, 2002; Tuzzi, 2009; Saloviita, 2018), finding mixed results. The results from the latter strand so far show that supported typing users have unique and idiosyncratic styles that differ from their assistants', but style idiosyncrasy does not rule out the possibility of assistants influencing the content of the texts produced (Saloviita, 2018). Linguistic analysis conducted by Zanobini and Emerson (2001; 2010) showed that textual output from supported typing contains linguistic patterns associated with both the assistant and the user. In the next chapters, we have the chance to further expand and comment specific segments of the FC literature that are related to the experiment conducted within this thesis' work.

In particular, in chapter 2 we will further into the literature on the linguistic analysis of texts produced via FC, while in chapter 3 we will focus on the literature on behavioural analysis of the FC dynamic and the ideomotor hypothesis.

1.6 Considerations on FC

In this chapter, we have provided a comprehensive overview of Facilitated Communication, defining and classifying it within the context of Assistive Technology. We have explored how FC, according to its proponents, is a technique designed to reduce users' motor limitations, thereby enabling them to communicate by supporting the pointing gesture required for typing. We then traced the origins and development of FC, introducing related techniques such as RPM, which share similarities with FC. Finally, we introduced the controversies that have fuelled the ongoing debate around FC, particularly regarding the authorship of the texts produced through the technique. Despite the scientific community's official statements against FC, which firmly discourage its use, this debate persists. The continued discourse is likely due to the widespread use of FC globally, even though it has not met evidence-based practice standards.

Determining why techniques like Facilitated Communication continue to be used is a complex issue with no simple or unifying answer, as the reasons vary depending on whether we consider the perspectives of practitioners or caregivers and users. The persistence of FC can be attributed to several factors, including reinforcement from practical experiences, anecdotal evidence suggesting authorship, and perceived behavioural changes in users after FC is introduced. Additionally, the deep emotional impact on families and caregivers, who are eager to believe in any method that promises communication breakthroughs, plays a significant role. Occasional research that challenges mainstream scepticism by demonstrating some level of user contribution further reinforces FC's application. Once FC has been introduced, these intertwined factors make it difficult for individuals to step back, despite the lack of robust scientific support.

In this context, it is crucial to note that the overall discussion on FC has frequently been reduced to the sole question of who is producing the text—who is doing the typing—without adequately exploring the technique itself. This narrow focus has neglected to address the various levels of user contribution, potential developmental trajectories, and the intrinsic dynamics between the user and facilitator. As a result, the communicative output has become the primary focus of FC investigations, leaving the underlying mechanisms, such as how text is constructed and the extent of user and facilitator involvement, largely unexplored. Additionally, the neurophysiology behind touch-based support and any potential developmental benefits associated with FC have been insufficiently examined.

By concentrating research efforts solely on the final output of FC, the debate has inevitably become polarized, deepening the divide between proponents and sceptics. This polarization has hindered the development of a middle ground for exploring and discussing the strengths and limitations of FC, as well as potential modifications and updates to the technique. The growing gap between proponents, who have kept presenting FC as a means of uncovering hidden communicative abilities, and sceptics, who focus solely on debunking claims of authorship, has stifled the bottom-up development of the technique, leading to its uncontrolled and uninformed application.

With such premises, our work aims to create space for a middle ground where FC can be reframed and explored beyond its immediate communication goals. We seek to investigate FC as a tool for the co-construction of textual output and the development of literacy and typing skills, moving beyond the current polarized debate. Furthermore, we seek to probe the potential benefits of touch-based support for individuals with DD, by investigating possible neurophysiological pathways of touch support.

1.7 Thesis outline

This thesis can be divided into two parts.

In the first part, chapters 2 and 3 investigate the broader implications of supported typing techniques, moving beyond mere communication. Through linguistic and behavioural analysis, it examines both the linguistic contributions of users to text production and their engagement levels during the typing tasks. In both these studies, we start from the maximal sceptic position to test the hypothesis that facilitators may subconsciously influence users' gestures, while users themselves may not actively contribute.

In chapter 2 we adopt a distant reading perspective (Moretti) to look for stylistic patterns in texts produced through Facilitated Communication over a decade. There we adopt quantitative measures of text analysis to detect users and facilitators stylistic fingerprints in the text produced. The chapter reports the results of two studies. In Study 1, we report the analysis of text written by different users sharing the same facilitator. In Study 2, we analysed text written by different users sharing at least two different facilitators. There we looked for evidence of persisting stylistic fingerprints independent from the source of the physical support. In the conclusion of chapter 2 we introduce the possibility of interpreting FC texts as the results of a co-creation process. The implications of the co-creative dynamic on FC applications and its developmental value are then discussed.

In chapter 3 we address FC from an opposite perspective: a close reading perspective where the object of analysis is each single pointing gesture towards the keyboard. In this chapter we investigate the levels of users' motor and linguistic involvement during the typing tasks. Starting from ideomotor perspective, this study explores four levels of user engagement: no contribution, motor-only (where the content is influenced by the facilitator), motor-linguistic (where the user contributes linguistically), and full communicative intent by analysing FC users' manual and eye movements.

Finally, the chapter discuss the potential of FC as mean towards the development of linguistic and literacy skills.

In the second part, chapters 4 and 5 address a possible neurophysiological mechanism that could account for the efficacy of touch-based support.
In chapter 4 we synthesized various strands of literature to propose a neural pathway through which touch could alleviate cognitive load during postural tasks, thereby freeing up cognitive resources for higher-order cognitive functions.
Chapter 5 puts this theoretical framework to the test through an fNIRS experimental task, wherein participants of varying ages and levels of cognitive impairment perform simultaneous postural and cognitive tasks with and without haptic feedback.
The concluding Chapter 6 consolidates the thesis's findings and propose a newer definition of FC within the AT domain, where user participation and literacy development take precedence over autonomous communication. Furthermore, it advocates for deeper exploration of touch support's facilitating role in the context of DD, not only in relation to existing assistive techniques but also in the development of innovative assistive and rehabilitation programs.

CHAPTER 2: INDIVIDUALS WITH DEVELOPMENTAL DISABILITIES MAKE THEIR OWN STYLISTIC CONTRIBUTIONS TO TEXT WRITTEN WITH PHYSICAL FACILITATION[1]

2.1 Introduction

Chapter 1 introduced Facilitated Communication, by classifying the technique within the context of Assistive Technology, by describing its origin and by introducing the controversies and the debate that surround its use and application.

The end of chapter 1 provides an outline of the goal of the thesis which is two folded. On the one side the thesis aims at providing an analysis of the FC dynamic with a greater interest in acknowledging different levels of user contribution, on the other it aims at evaluating the underlying neurophysiological pathways of touch-based support (a grounding feature of FC).

The first goal is pursued by chapter 2 and chapter 3, while the second goal is addressed by chapter 4 and chapter 5.

This chapter describes an attempt to use quantitative linguistic analysis to investigate whether DD users typing text with touch assistance exhibit their own stylistic signatures alongside those of their facilitators. We start by providing a careful analysis of the studies that have addressed the FC debate through linguistic methods. Then we propose two separate studies: in Study 1, we investigate whether the stylometric fingerprints of a set of users are detectable when they are all assisted by the same facilitator. In Study 2, we examine whether the users' stylometric characteristics are retained even when they are assisted by multiple facilitators.

Linguistic analysis of FC users' text have found unexpected or unusual lexical choices (Zanobini and Scopesi, 2001; Niemi and Kärnä-Lin, 2002), linguistic idiosyncrasies (Biklen et al., 1991; Zanobini and Scopesi, 2001; Scopesi, 2003), spelling errors (Biklen et al., 1991; Janzen-Wilde et al., 1995), unusual syntax (Biklen et al., 1991; Niemi and Kärnä-Lin, 2002) and differences in terms of MLU (medium length utterance) when compared with texts written by facilitators (Scopesi, 2003). These results appear to suggest some active involvement of the user in the text production process.

In terms of the properties of the generated text, studies conducted within the EASIEST project (Bernardi, 2008; Cortelazzo, 2008; Di Benedetto, 2008; Tuzzi, 2008, 2009; Bernardi and Tuzzi, 2011a, 2011b) used hierarchical clustering methods to show that FC users' texts were stylistically

[1] The work presented in this chapter is also part of the published paper: Nicoli, G., Pavon, G., Grayson, A., Emerson, A., Cortelazzo, M., and Mitra, S. (2023b). Individuals with developmental disabilities make their own stylistic contributions to text written with physical facilitation. Frontiers in Child and Adolescent Psychiatry.

different from those of their facilitator, as indicated by a different ratio in the use of adjective and adverbs (Tuzzi, 2008), an increased number of low-frequency word neologisms and adverbs with the Italian /-mente/ suffix (Benelli and Cemin, 2008; Cortelazzo, 2008), and -frequent use of figures of speech such as anastrophe, "tmesi", metaphors, and word inversions (Di Benedetto, 2008). As pointed out by Saloviita (2018), differences in style between FC users' and facilitators' texts does not prove that users are the true authors of the texts they produce. It could be argued that text produced by FC users with the facilitator's assistance might be different in style to text produced by FC users without assistance. This scenario is not testable as users adopt FC because they cannot type independently, but it is consistent with Pennebaker's (2011) synergy hypothesis defining the stylistic features of texts produced by multiple authors. Each author involved in the co-creative process is expected to lose their own stylistic fingerprint, creating different stylistic features in the co-created text. Besides, facilitators may simply change their own writing style when involved in the FC process as suggested by Saloviita (2018) and Eder (2018).

Rather than trying to address stylistic differences between FC users and facilitators when they operated individually, Emerson (2010) considered whether the signatures of both might be embedded in the text they produce together. This approach revealed occurrences of lexical choices that could be linked to the user (words used only by the same user with different facilitators) alongside those that were linked to the facilitator (words used by different users only when assisted by the same facilitator). Such results suggest that FC texts are co-constructed by the user and facilitator (Duchan, 1999; Zanobini and Scopesi, 2001). The plausibility of the co-construction hypothesis depends upon indications of co-authorship at the levels of lexical choice, syntactical patterns (use of function words and word sequences), distribution of morphological markers and phonological/graphemic patterns (through the analysis of short sequence of characters). The potential value of such co-authored text for the communicative, educational, or cognitive and emotional growth of individuals facing the multi-faceted challenges of developmental disabilities is a separate issue, to which we return in the discussion.

Quantitative methods of linguistic analysis offer several ways to investigate contributions to authorship within corpora of text. Stylometry measures concrete, discrete, non-linear and even non-linguistic (Juola, 2008) textual features to identify authors' 'fingerprints' (Stamatatos, 2009). The linguistic fingerprints can then be compared to address authorship attribution issues. Stylometry allows a "distant reading" (Moretti, 2005) of texts, enabling the quantification and comparison of broad textual patterns that are unlikely to be consciously manipulable. One approach is to create a simplified model, such as the bag-of-words, whereby texts are considered as lists of words or character n-grams (sequences of characters of different size), sorted by frequency. Each word appearing within the text is a dimension and its frequency the value along that dimension. Casting pieces of text as vectors occupying locations in a space enables a range of statistical analyses on the stylistic distance between the vectors.

It is very important to be careful with the term 'authorship' in this context. The attribution of authorship using stylometric analysis concerns patterns of language use. Stylometry cannot be used to query whether the thoughts expressed in the text are the author's own. This, however, is the sense of the term 'authorship' at the core of controversies about touch-assisted typing by individuals with DD. Stylometry applied to text written using FC cannot address whether the thoughts expressed in the text are the user's or the facilitator's. It can only detect the presence of stylistic patterns attributable to each. As such, 'authorship' and 'co-authorship' are used in this article in the stylometric sense, encompassing the syntactic, lexical, morphological, and phonological patterning of text.

One analysis approach uses unsupervised learning algorithms to calculate the distance between vectors. The shorter the distance, the closer the texts in stylistic features (in terms of lexical, morphological, or syntactic choices). Several algorithms have been proposed for calculating the distance between texts, starting with Burrows' delta or "classical delta" (Burrows, 2002; Hoover, 2004) to "cosine delta distance" (Jannidis et al., 2015; Evert et al., 2017), which computes a cosine similarity between a matrix of values normalized (z-scored) to minimize matrix size. Once the texts are organized in a distance table (with respect to their distances to other texts), their similarities can be expressed in multiple ways. Hierarchical clustering analysis, for example, displays texts in a dendrogram that progressively pairs them based on similarities. Thus, texts occupying the same leaf are highly similar. Another method of expressing stylistic relationships between texts is the bootstrap consensus network (Eder, 2017), which graphically displays stylistic similarities through linkages of varying thickness.

These stylometry methods can be valuable in investigating the issue of authorship of texts generated through AAC techniques such as FC as they provide a time-extended perspective on the text construction process as it operates naturally, without the insertion of experimental artifacts. The analysis of text generated over long periods of time, while the user and their partnership with facilitators evolve, provide a stronger test of individual influences than snapshot methods using arbitrary tasks in which the user possibly is not motivationally invested. Linguistic analysis may also address authorship questions at multiple levels: lexical, by investigating lexical choices, syntactical, by focusing on the use of function words and word sequences, morphological, by observing the distribution of morphological markers, and phonological/graphemic, by considering character n-gram patterns.

The focus of the present chapter is to conduct multi-level quantitative linguistic analyses of corpora of text generated by multiple FC users with the same facilitator (Study 1), and text produced by multiple users, each with multiple facilitators (Study 2), to determine whether, or to what extent, the FC users' stylistic signature can be detected alongside that of their facilitators. In both studies, we start from the maximally sceptical position that the facilitator is the sole ordering agent, and that text produced using FC is not objectively attributable to any source other than the facilitator. It should not be possible, then, to find unique stylistic fingerprints associated with specific FC users. We use unsupervised machine-learning methods, particularly cluster analysis, to test whether the stylistic distance between texts (based on intrinsic stylistic features) is governed solely by the characteristics of the facilitator. We first describe the characteristics of the texts that we analysed, and then present the two studies.

2.2 The Corpora

The texts analysed in the present studies were collected from two FC centres in Italy. The texts are therefore in Italian and have not been used previously in research. To accumulate a sufficient amount of data for each FC user, we collected pre-existing texts written over the past two decades in the course of each centre's usual practice. For the purpose of this project, we asked each centre to forward all the pre-existing texts produced by their clients that they had stored in their databases. The centres gave written consent for us to use their data in our analyses under the condition that our reports would be fully anonymized at the levels of the users, facilitators, and the centres. As the present work only reports fully anonymized analysis of pre-existing data, and we obtained consent from the holders of the data, we did not require ethical approval for these analyses.

In Centre 1 and Centre 2, the texts were stored in a specific folder named after each participant, each .docx file within each folder representing the text output of one FC session, held on a weekly basis. Most of the texts were in a dialogue form, therefore they contained lines from the user and lines from the facilitator (highlighted in caps lock). Each document identified the facilitator who assisted the FC session reported in it.

The texts were then pre-processed in the following steps.
First, the texts were divided by user-facilitator pairings. All the users from Centre 1 wrote with the same facilitator, but the users from Centre 2 were assisted by multiple facilitators. Second, the users' lines were automatically separated from facilitators' lines using a python script. Any references to the users' or facilitators' names were then removed from each file. Finally, all the files for each user-facilitator pairing were grouped into a unique .txt file and coded in UTF-8 to allow R software to run the analyses on the files. These operations created Corpus 1 for Centre 1 and Corpus 2 for Centre 2 (see Tables 2.1 I and 2.2 I). Corpus 1 had 7 participants (3 Female, 4 Male; Age: 19-44 yrs, mean = 25.8; > 10 yrs since FC adoption), and Corpus 2 had 10 participants (7 Female, 3 Male; Age: 21-54yrs, mean= 38.9; > 10 yrs since FC adoption). All the users involved in this study could not

communicate independently through writing and, in some cases, they were diagnosed with mild to severe intellectual disability. The users' information is shown in Table 2.3. The users' names were coded by assigning to each user a number (U1, U2, and so on). For Corpus 2, the facilitators' names were coded with the letter "F" followed by a progressive number (F1, F2 and so on). The users' and facilitators' names were separated by an underscore ("_"). According to the needs of the studies, these files were then assembled into different corpora created specifically to address the research questions (see the Materials section of each study).

Before addressing these texts quantitatively in Study 1 and Study 2, we consider both corpora in their entirety, focusing on the global characteristics of the writings of FC users. Corpus 1 is composed of 84001 occurrences (tokens, the number of total words used in the corpus) resulting from the use of 10552 words (types, number of different forms that appears in the corpus). Corpus 2 consists of 481228 occurrences (tokens) resulting from the use of 20021 words (types).

Corpus 1	Words	Types
U1	20449	3865
U2	11631	2772
U3	13568	3162
U4	12379	3257
U5	15564	3479
U6	3370	1203
U7	7040	2142

I

Corpus 1_A	Words	Corpus 1	Words	Corpus 1	Words
U1_1-2	10268	U1_1-3	10293	U1_1-4	10196
U1_3-4	10210	U1_2-4	10185	U1_2-3	10282
U2_1-2	5934	U2_1-3	5955	U2_1-4	5674
U2_3-4	5724	U2_2-4	5703	U2_2-3	5984
U3_1-2	7052	U3_1-3	7173	U3_1-4	6472
U3_3-4	6542	U3_2-4	6457	U3_2-3	7122
U4_1-2	6476	U4_1-3	6469	U4_1-4	5974
U4_3-4	5932	U4_2-4	5939	U4_2-3	6434
U5_1-2	8363	U5_1-3	8270	U5_1-4	7247
U5_3-4	7231	U5_2-4	7325	U5_2-3	8347

II

Table 2.1. Corpora from Centre 1. I. Corpus_1. Texts collected from Centre 1. All texts were written with a single facilitator. II. Corpus 1_A, Corpus 1_B, and Corpus 1_C. The text production of each user, after being divided in four homogeneous chunks, is merged in three different ways. In Center1_A, the first chunk is merged with the second chunk, and the third and the fourth chunks are merged together. In Center1_B, the first chunk is merged with the third, and the second and the fourth chunks are merged together. In Center1_C the first chunk is merged with the fourth, and the second and the third chunks are merged together.

Corpus 2	Words	Types
U8_F1	17710	2727
U8_F2	5007	1430
U8_F3	18091	2834
U9_F1	28857	3494
U9_F2	6438	1721
U9_F4	6065	1454
U10_F1	16192	3035
U10_F2	47476	6113
U10_F4	6961	1940
U10_F8	25718	3913
U11_F1	21829	3300
U11_F2	11586	2560
U12_F1	22927	3892
U12_F2	15337	3516
U12_F5	5100	1229
U12_F7	27634	4962
U12_F8	6395	1700
U13_F1	12954	2177
U13_F3	7750	1663
U14_F1	64202	5738
U14_F5	5464	1321
U15_F1	38549	3531
U15_F3	5021	1172
U16_F1	14575	2061
U16_F2	8816	1994
U16_F3	24654	3273
U17_F1	5705	1492
U17_F8	4954	1470

I

Corpus 2_	Words
U8_F1	17710
U9_F1	28857
U10_F1	16192
U11_F1	21829
U12_F1	22927
U13_F1	12954
U14_F1	64202
U15_F1	38549
U16_F1	14575
U17_F1	5705

II

Corpus 2_1_A	Words	Corpus 2_1_B	Words	Corpus 2_1_C	Words
U8_1-2	9073	U8_1-3	9090	U8_1-4	8678
U8_3-4	8642	U8_2-4	8625	U8_2-3	9037
U9_1-2	14372	U9_1-3	14538	U9_1-4	14285
U9_3-4	14491	U9_2-4	14325	U9_2-3	14578
U10_1-2	8481	U10_1-3	8332	U10_1-4	7988
U10_3-4	7716	U10_2-4	7865	U10_2-3	8209
U11_1-2	11195	U11_1-3	11151	U11_1-4	10604
U11_3-4	10639	U11_2-4	10683	U11_2-3	11230
U12_1-2	11743	U12_1-3	11625	U12_1-4	11283
U12_3-4	11189	U12_2-4	11307	U12_2-3	11650
U13_1-2	5423	U13_1-3	6147	U13_1-4	5626
U13_3-4	7537	U13_2-4	6813	U13_2-3	7334
U14_1-2	31566	U14_1-3	32812	U14_1-4	33806
U14_3-4	32642	U14_2-4	31396	U14_2-3	30402
U15_1-2	17690	U15_1-3	17853	U15_1-4	17799
U15_3-4	20866	U15_2-4	20727	U15_2-3	20757
U16_1-2	7572	U16_1-3	7607	U16_1-4	6889
U16_3-4	7008	U16_2-4	6973	U16_2-3	7690

III

N° of total words			
Facilitators	Words	Users	Words
F1	243500	U8	40808
F2	94660	U9	41360
F3	55516	U10	96347
F4	13026	U11	33415
F5	10564	U12	77393
F7	27634	U13	20704
F8	37067	U14	69666
		U15	43570
		U16	48045
		U17	10659

IV

Table 2.2. Corpora from Centre 2. I. Corpus_2. Texts collected from Centre 2. Users were assisted by multiple facilitators. II. Corpus 2_1. Texts from Corpus 2 written solely with F1. III. Corpus 2_1_A, Corpus 2_1_B, and Corpus 2_1_C The text production of each user, after being divided into four homogeneous chunks, is merged in three different ways. In Corpus 2_1_A, the first chunk is merged with the second chunk, and the third and the fourth are merged. In Corpus 2_1_B, the first chunk is merged with the third, and the second and the fourth chunks are merged together. In Corpus 2_1_C, the first chunk is merged with the fourth, and the second and the third are merged together. IV. A summary of the total words available for each user (independently of the facilitator) and each facilitator (independently of the user). Note that nearly half of the words collected in Centre 2 were typed with the assistance of facilitator 1 (F1).

Participant	Gender	Age	Diagnosis	Experience with FC	Level of facilitation (to date)
U1	Female	25	ASD	21	Shoulder
U2	Male	20	Expressive language disorder	13	Elbow
U3	Male	26	ASD	17	Shoulder
U4	Male	22	Cerebellar ataxia	11	Hand
U5	Female	20	Intellectual disability	8	Wrist
U6	Female	42	ASD	26	Wrist
U7	Male	44	Autism	20	Elbow
U8	Female	47	Down Syndrome	18	Elbow
U9	Female	44	Cromosomic alteration	18	Hand
U10	Female	34	Tuberous sclerosis	18	Hand
U11	Female	47	Cerebral Palsy	16	Hand
U12	Male	56	Severe mental retardation	18	Hand
U13	Male	36	Encefalopathy	14	Forearm
U14	Male	52	Severe mental retardation	10	Hand
U15	Female	24	Severe mental retardation	10	Hand
U16	Female	28	Cerebral Palsy	14	Hand
U17	Female	39	Cerebral Palsy	15	Hand

Table 2.3. Description of FC Users. For each FC user, gender, age, diagnosis, years of FC use and the actual level of facilitation are shown. Users U1 - U7 came from Centre 1, and users U8 - U17 from Centre 2. All the users reported in the table could not communicate independently through writing. Note that the terminology that was used in the original diagnoses is retained in this table.

According to Bernardi (2008), the linguistic production resulting from a process of Facilitated Communication presents some peculiarities that separate it from neurotypical communication. Some characteristics appear to have nothing idiosyncratic or individual (Di Benedetto, 2008) about them, and appear instead to be a trait common to the population who write with FC. The peculiarities of the (Italian) language of Facilitated Communication, explored in Cortelazzo (2008), Benelli and Cemin (2008) and Di Benedetto (2008) can be summarized as follows: (1) the presence of a varied and non-repeating lexicon, with the presence of numerous Hapax legomena (words that appear- just once in the corpus), (2) the occurrence of uncommon words of the Italian language, (3) the use of common words isolated from their context of natural occurrence, (4) the presence of words that do not exist in the Italian language but are possible, (5) frequent use of forms with the prefix / in /, (6) the intensified use of adverbs in / -mente /, (7) the presence of marked syntactic structures alongside unmarked syntactic structures, and (8) strong incidence of left-side dislocations (focalization of a word by putting it first in syntactical construction).

The texts of Corpus 1 and 2 have many features in common with the texts of the EASIEST project (2008). Corpus 1 and 2 exhibit a non-repetitive and rich lexicon, and also behave in a similar way to the texts used in Bernardi (2008) with regard to uncommonly used word forms. The analysis with respect to the frequency of the different words, conducted with the CoLFIS (2005) software shows that there are numerous uncommon forms within the corpus. Thus, among the words of uncommon use, as in those of common use, the presence of numerous forms introduced by the in- negative prefix is confirmed. As described in Bernardi (2008), it is also possible to identify some words within Corpus 1 and 2 that are not part of the Italian language lexicon but which are possible as they are constructed according to the rules of word formation. Among these, it is possible to notice that the adjective formation from a nominal base through the suffix /-oso/ is very frequent and used correctly in most cases to indicate the presence and abundance of the quality expressed by the name from which it derives. Similarly, we noted the tendency to form denominal verbs (for example "vacanzare") or de-aggettival (for example "tristeggiare"). Finally, the production of new possible words is productively originated through the creation of adverbs in /-mente/: in the corpus we can in fact observe forms such as "narcisamente" (narcissistically), not present in the Italian vocabulary.

From a syntactical standpoint, we noticed that in Corpus 1 and 2 there are sentences with a marked syntactic structure, although less frequent compared to the texts described in Bernardi (2008). It is possible to observe constructions that are freed from the SVO structure through the anticipation of the second argument or the postposition of the predicate (see examples 1-4 below), by reversing the noun adjective order (examples 5, 6), or by avoiding articles and other grammatical elements (examples 7,8,9). However, the incidence of these marked structures is lower than that described in the EASIEST research. These could be the sign of a higher editorial intervention from the facilitators or the result of a process of style development or teaching within each Center. Examples:

1. “suoni buoni faccio” (U15_F1) [I make good sounds]
2. “forte molto grande mi sembra” (U14_F5) [It seems very big and strong]
3. “bravi e testardi operatori ho trovato” (U17_F8) [I found good and stubborn operators]
4. “io donna silenziosa sono” (U9_F2) [I am a silent woman]
5. “sono come vulcanosi monti ormai svuotati che hanno bruciato le loro emozioni” (U9_F4) [I am like vulcanous but emptied mountains that have burned their emotions]
6. “forte senso di piacere nei rigidi muscoli” (U11_F2) [strong sense of pleasure in rigid muscles]
7. “io dico che importante problema si verifica” (U12_F5) [I say that it is verifying an important problem]
8. “rabbioso momento interno mi ha colpito” (U13_F3) [a rabid internal moment hit me]
9. “gambe non aiutano ma mani si” (U16_F2) [legs do not help, but hands do]

2. 3 Study 1

In this study, we investigate the stylistic characteristics of text produced over 10 years by sets of FC users each working with the same facilitator. We collect and separately analyse, using identical methods, texts from two independent FC centers in Italy. The users in each center produced their texts with a single facilitator. Our null hypothesis is that texts from each center carry a single stylistic influence – the facilitator. As the FC user is not a significant linguistic agent in this view, texts produced by an individual user are not expected to be more similar to other texts by the same user than to texts by other users. We use unsupervised machine-learning techniques to carry out this similarity analysis. To allow user-to-user comparison, we split each user’s text into two chunks of equal length in three different ways. We then measure the stylistic distance between texts and display them on cluster dendrograms. If the facilitator is the sole stylistic agent at each center, the clusters should exhibit no user-related grouping, with texts by the same user unlikely to be paired at the leaf level of the dendrogram.

2.3.1 Materials

As previously introduced, Corpus 1 consisted of seven users’ texts written with a single facilitator. From Corpus 2, texts that were written with Facilitator 1 (who was the facilitator most represented in the corpus) were selected to create Corpus 2_1 (Table 2.2 II), which consisted of 10 users’ texts. Thus, the included users from both Corpus 1 and 2 had written with a single facilitator at their Center, and each user’s text was more than 5000 words in length (Eder et al., 2016)

For cluster analysis, each text was split into 4 equal-length fragments that were subsequently assembled in three different ways to create two equal-length chunks for each text. The chunking was done using different combinations of text fragments, and the analyses repeated for each method of chunking, so that the results could not be dependent upon the accident of a specific chunking approach. First, the texts were merged chronologically (thus, fragment 1 and fragment 2 created chunk 1-2, and fragment 3 and fragment 4 created chunk 3-4). This constituted Corpus 1_A and Corpus 2_1_A (recall that Corpus 2_1 contained texts from Center 2 that were written with facilitator 1). Second, chunks were created by joining fragments 1 and 3 (chunk 1-3) and fragments 2 and 4 (chunk 2-4). This created Corpus 1_B and Corpus 2_1_B. Finally, fragments 1 and 4 were merged to give chunk 1-4 and fragments 2 and 3 gave chunk 2-3. The results of these operations were Corpus1_C and Corpus 2_1_C. As seen in Tables 2.1 I and 2.2 I, the division of U7 and U17's texts would result in chunks of less than 5000 words. These users were therefore not included for cluster analysis. The texts were named after the user's code and a numerical code referring to the merged chunks (for example, U1_1-2 signified chunks 1 and 2 of U1 merged). The corpora are displayed in Table 2.1 II for Centre 1 and Table 2.2 III for Centre 2.

2.3.2 Methods

Corpus1_* and Corpus 2_1_* were analyzed separately using the clustering method implemented within Stylo for R (Eder et al., 2016). The analysis was performed based on the first 1000 most frequent words and on the first 1000 most frequent character-trigrams. Textual distance was calculated using cosine delta distance (Jannidis et al., 2015).

2.3.4 Results

The cluster analysis (Figs 2.1 and 2.2) showed that texts by the same user consistently produced the closest pairing. In the case of Corpus 1_* (Fig 2.1), whether using the 1000 most frequent words or character-trigrams, the closest pairings were always of texts by the same user. This was also the case for Corpus 2_1_* (Fig 2.2) using words, but there was one notable exception in the analysis by character-trigrams. In one of the three ways of splitting users' text (Corpus2_1_A, where the first two quarters of each user's text were separated from the last two quarters), one of U12's chunks (U12_1-2) was grouped with U11's texts, and the other (U12_3-4) was grouped with U14's texts. This suggests the possibility that U12's style is similar to U11 and U14.

It is also interesting to note the pair relationships across the dendrograms. In the case of Corpus 1_* (Fig 2.1), U1 is consistently on the lowest, most distant branch. In the upper branch, U2 and U3 are grouped the closest, followed by U5 and U4. This pattern of similarity between users is stable across all three ways of separating their texts and analysis by the most used words or character-trigrams. In the case of Corpus 2_1_* (Fig 2.2), U10, U11 and U12 always occupy the inferior major branch, separated from all the other users. U15 and U16 are often paired together, as are U13 and U14.

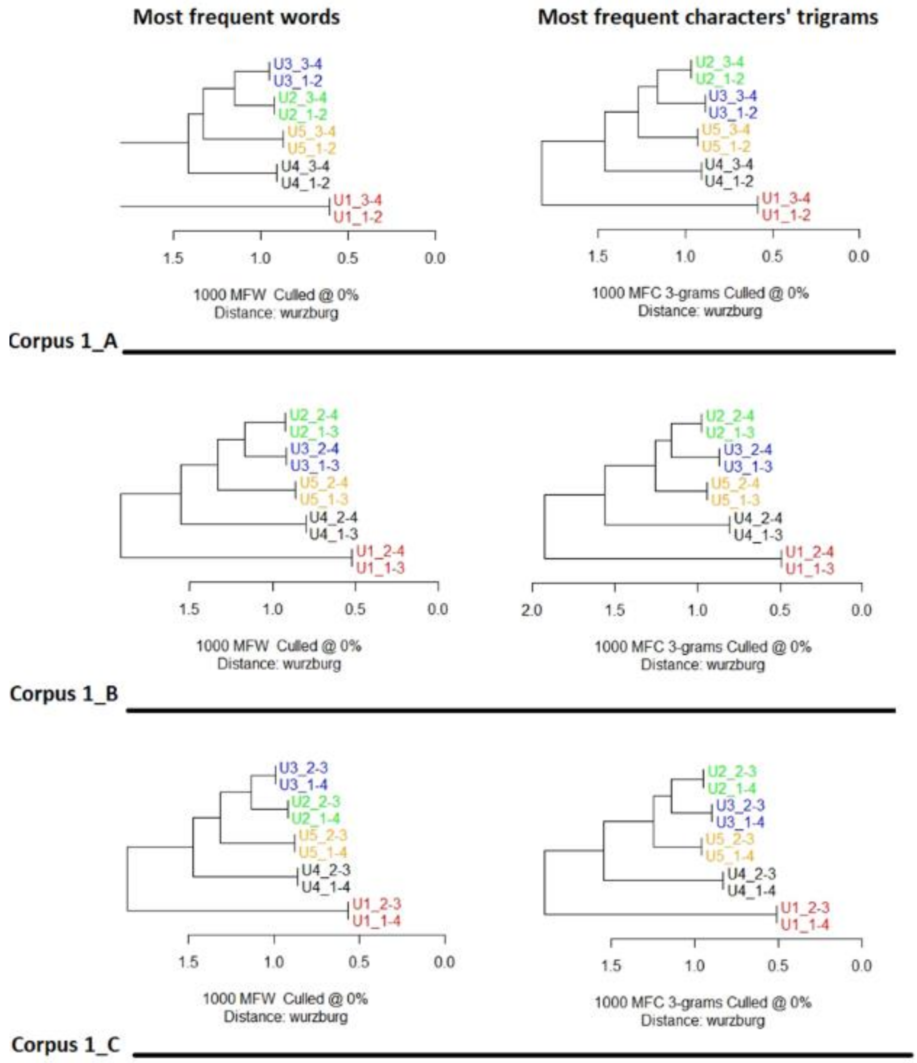


Fig 2.1. Cluster analysis of texts from Corpus 1_A, Corpus 1_B and Corpus 1_C. Features' selection 1000 most frequent words (left column) and 1000 most frequent characters' trigrams (right column). Distance: cosine delta. Texts were firstly divided into 4 quarters, then reassembled in three different ways. The code following the underscore indicates the merged quarter. Thus U3_1-2 indicates the first and second texts' quarters of participant 3 merged together. In all conditions and features' selection texts of the same user are systematically, paired together at dendrograms' leaves level. U1 occupy singularly one of the two major branches, opposed to all the other users.

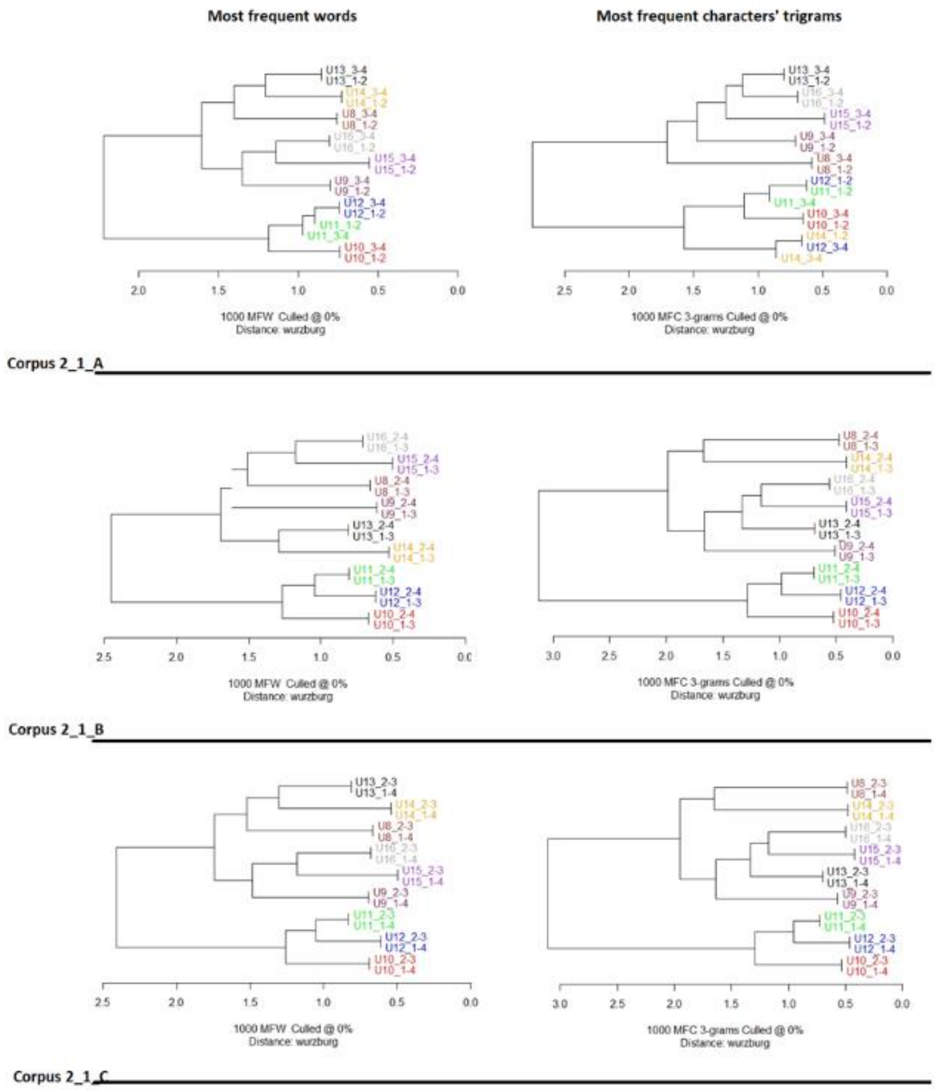


Fig 2.2. Cluster analysis of texts from corpora Corpus 2_1_A, Corpus 2_1_B and Corpus 2_1_C. Features' selection 1000 most frequent words (left column) and 1000 most frequent characters' trigrams (right column). Distance: cosine delta. Texts were firstly divided into 4 quarters, then reassembled in three different ways. The code following the underscore indicates the merged quarter. Thus U13_2-3 indicates the second and the third texts' quarters of U13 merged together. In all conditions and features' selection texts of the same user are systematically paired together at dendrograms' leaves level, with the sole exception of Corpus 2_1_A characters' trigrams where participant U12 is paired once with U11, once with U14. Two major users' groups are displayed. U13, U14, U15, U16, and U8 on the one side, U9, U11, U12, and U10 on the other.

2.3.5 Summary

The study set out with the assumption that the facilitator is the sole stylistic influence on each of the two corpora. If this was the case, the cluster analysis results would not be expected to show any pattern of stylistic similarities between texts. This would apply both to the similarity between chunks of text by the same user and to the stylistic proximity of texts across users. The cluster analysis results were not consistent with the starting assumption. As is clear from Figs 2.1 and 2.2, chunks of text by the same user were almost perfectly grouped together, suggesting that the unsupervised machine-learning algorithm could reliably detect the unique stylistic signature of most of the users. There were also clear and stable patterns of differential similarity between users, which is also not consistent with the starting hypothesis.

2.4 Study 2

In Study 1, we considered texts from multiple users who worked with the same facilitator. For both the FC centres from which we collected texts, we tested and rejected the hypothesis that the facilitator was the sole detectable stylistic influence on the texts produced by users at each centre. In this study, we analyse texts produced over a period of 10 years by FC users who were assisted by a pool of facilitators, each user working with multiple facilitators. From Centre 2 (introduced in Study 1), we included texts of users who wrote consistently with at least two facilitators. As in Study 1, our starting hypothesis was that only the facilitators' stylistic characteristics should be distinguishable in the corpus. As, in this view, the users have no stylistic signatures of their own, texts by different users should group only according to the facilitators who assisted their production. Equally, texts by the same user with different facilitators should also group only with the facilitators. As in Study 1, we use unsupervised machine-learning to organize the texts by stylistic similarity. We consider all the texts that were produced by each user-facilitator pairing and investigate the extent to which texts group according to the facilitator. If the facilitators are the only contributors to the stylistic characteristics of these texts, then we should not see any indications of similarity between texts by the same user.

2.4.1 Materials

For this study, we used texts from Corpus 2 (Table 2.2 I) as this corpus satisfied the conditions we wanted to test. As many FC users at Centre 2 have typed texts with the assistance of multiple facilitators, it was possible to consider texts of more than 5000 words written by FC users who had written consistently (>5000 words) with at least two different facilitators. Corpus 2 contains 28 pieces written by 10 FC users with 7 different facilitators. As is clear from Table 2.2 (I), texts for each user-facilitator pairing were longer than 5000 words, but the sizes were not balanced. The distribution of facilitators and the number of words typed with their assistance was uneven as well. F1 assisted all ten users (243500 words), F2 six users (94660 words), F3 four users (55516 words), and so on.

2.4.2 Methods

The key question in this study is: do texts written by users with the assistance of multiple facilitators show that the only detectable stylistic signature is that of the facilitator? This question was addressed through two methods, reported in Study 2A and Study 2B. In study 2A, Corpus 2, was analyzed using the hierarchical clustering mechanism implemented in Stylo for R (Eder et al., 2016). The analysis was conducted on both the 1000 most frequent words and the 1000 most frequent character-trigrams. Cosine delta distance was adopted as the measure of distance (Jannidis et al., 2015; Evert et al., 2017). The cluster analysis returned a distance table where, for each text, its distance from all the other texts involved in the analysis is computed. Since the analyses by words and trigrams produced very similar results, we have reported the analysis by words only.

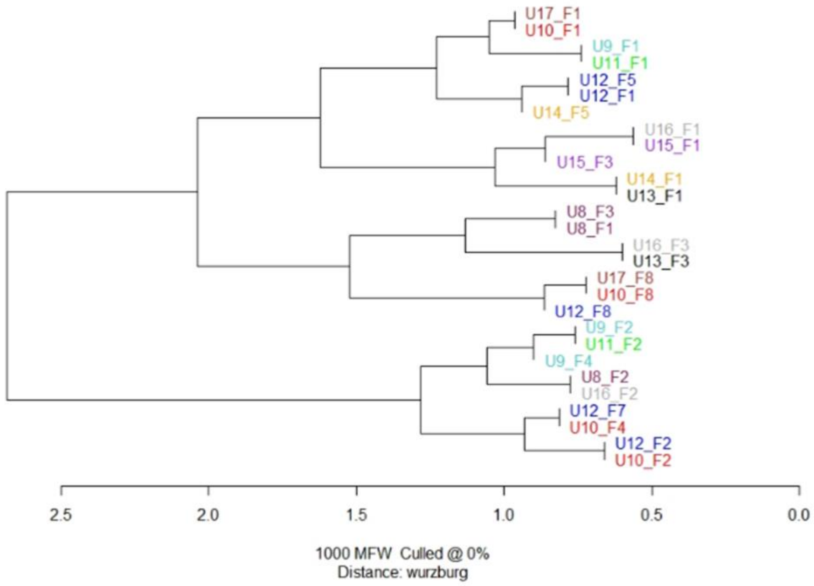
In study 2B, Corpus 2 was analyzed using the bootstrap consensus network method implemented in Stylo for R (Eder et al., 2016). The bootstrap consensus network was used to highlight all the relationships existing between texts that could not be visualized in the dendrogram, nor quantified by distance tables. The bootstrap consensus network allows a multiple and progressive evaluation of the corpus using different sets of features (Eder, 2018), in this context vectors of most frequent words ranging from 100 up to 5000. Again, this analysis conducted with character bigrams and trigrams yielded very similar results and so are not separately reported. Cosine delta distance was used to compute text similarity, as it is known to provide highly reliable results (Jannidis et al., 2015; Evert et al., 2017)

2.4.3.1 Study 2A: Cluster analysis

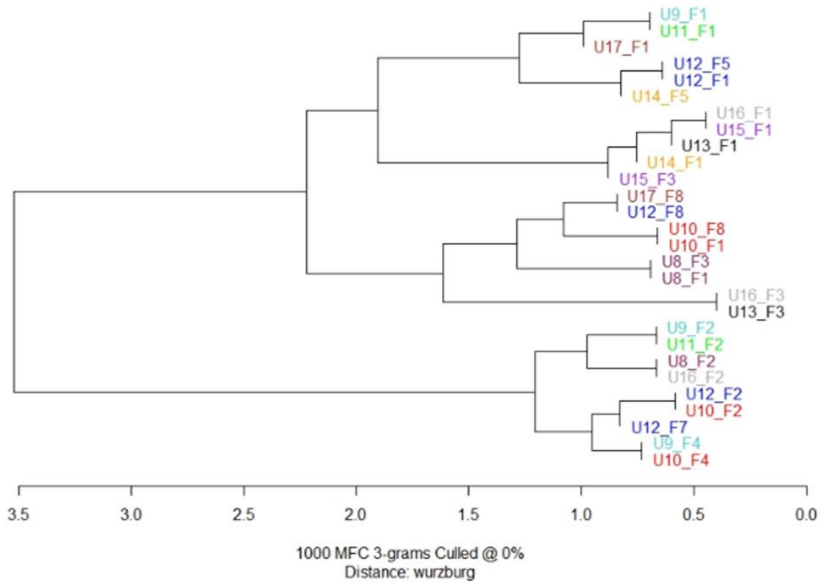
When texts by each user-facilitator pairing are considered, texts mainly group according to the facilitator rather than the user (Fig 2.3). However, the distance table associated with this cluster analysis showed patterns that are not seen in the dendrograms. Since words and trigrams distance tables provide similar results, we concentrated just on the words analysis.

The ranking of each text was analyzed to look for patterns of similarities between texts. If *n* is the number of texts written with the same facilitator, and the facilitator is the only stylistic source in these texts, the distance table should place in the first *n*-1 positions only those texts that shared the same facilitator. In the case of the user-facilitator pair U8_F1, for example, as facilitator 1 assisted in 10 texts, the first nine positions of similarity (i.e., rows in the distance table) should be occupied by the other texts written with facilitator 1 (that is, U9_F1, U10_ F1, U11_ F1, U12_ F1, U13_ F1, U14_ F1, U15_ F1, U16_ F1, and U17_ F1). The *n*-1 value for each facilitator (reflecting the number of users they assisted) is graphically displayed in the Table 2.4 by a thick red line (*n*=10 for F1, *n*=6 for F2, *n*=4 for F3, *n*=2 for F4, and *n*=3 for F8; F7 worked with only one user).

If the users made no stylistic contribution, their texts should rank randomly below the *n* value for each facilitator. This red line represents the landmark we refer to in our observations. Texts of the same user (expressed by each column) that rank above the red line, are coloured red. Similarly, texts that rank below the red line are reported in orange if they belong to the user expressed by the column. The analysis of texts that rank below the red line is particularly interesting for those facilitators that are less represented (as F7). In those cases, since a smaller number of texts could rank above the red line, the ranking of texts that come right below is worth noting.



I



II

Fig 2.3. Corpus 2 cluster analysis. Features' selection: 1000 most frequent words (I) and 1000 most frequent characters trigrams (II). Distance: Cosine Delta. Clustering ratio seems to be facilitator dependent. Texts written with the same facilitator are, in fact, grouped together. For example, texts written with facilitator 1 occupy mainly the upper branch of the dendrogram, while texts written with 2 occupy the lower one.

As we can see from distance tables (Table 2.4), 27 texts breach the red line, which means that the users' stylistic contribution in 27 out of 60 cases breach the facilitator-influence barrier, contrary to what is expected from the null hypothesis. Moreover, in 22 cases, the user's texts classify in the first three rank positions, on 32 in the first 5 rank positions, and on 54 occasions out of 60 in the first 10 rank positions. On 11 occasions, texts of different users and facilitators also breach the red line. In most of these cases, the users are the same as the ones that occur in the first rank positions. Consider for example U8_ F1. In the first two rank positions, we find U16_ F1 and U14_ F1. Then at rank 7 and 9 we find respectively U16_ F3 and U14_ F5. Since U8_ F1 is very similar to U16_ F1 and U14_ F1, its similarity with U16_ F3 and U14_ F5 may be due to inter-user stylistic similarity; texts representing the same user but not the same facilitator (i.e., not the one expressed by the column) that rank above the red line might indicate inter-user similarities, as between U8 and U16, that are not determined by the facilitator's influence.

Another aspect that is worth noting is that texts of the same user (i.e., the one expressed by the column) rank above all the other texts written with the same facilitator (56/60, see Table 2.8). Consider U8_ F1 as an example. U8_ F3 is the first text written with F3 in the ranking; also, U8_ F2 is the first text written with F2 that appears in the distance table relative to U8_ F1. This happens systematically for all texts' relationships and shows that it is the user's contribution, rather than the facilitator's one, that determines the similarity. If no stylistic contribution is made by the user, these consistent and systematic patterns of rankings should not occur; texts by the same user written with different facilitators should rank randomly.

Rank	U8_F1	U9_F1	U10_F1	U11_F1	U12_F1	U13_F1	U14_F1	U15_F1	U16_F1	U17_F1
1	U16_F1	U15_F1	U10_F8	U9_F1	U11_F1	U14_F1	U13_F1	U16_F1	U15_F1	U12_F1
2	U14_F1	U11_F1	U10_F2	U12_F1	U12_F5	U15_F1	U15_F1	U9_F1	U8_F1	U11_F1
3	U15_F1	U13_F1	U10_F4	U10_F1	U14_F1	U16_F1	U12_F1	U15_F3	U13_F1	U14_F1
4	U8_F3	U16_F1	U11_F1	U14_F1	U12_F7	U9_F1	U8_F1	U13_F1	U9_F1	U16_F1
5	U13_F1	U15_F3	U8_F1	U17_F1	U12_F2	U8_F1	U9_F1	U14_F1	U14_F1	U15_F1
6	U10_F1	U14_F1	U12_F1	U11_F2	U17_F1	U13_F3	U16_F1	U8_F1	U16_F3	U10_F1
7	U16_F3	U9_F2	U17_F1	U13_F1	U10_F1	U15_F3	U11_F1	U17_F1	U15_F3	U12_F5
8	U9_F1	U9_F4	U14_F1	U15_F1	U12_F8	U11_F1	U17_F1	U11_F1	U17_F1	U9_F1
9	U14_F5	U8_F1	U12_F2	U16_F1	U13_F1	U12_F1	U15_F3	U10_F1	U13_F3	U8_F1
Facilitator's line										
10	U17_F1	U17_F1	U12_F5	U9_F4	U10_F4	U14_F5	U14_F5	U13_F3	U11_F1	U13_F1
11	U17_F8	U14_F5	U16_F1	U12_F5	U14_F5	U17_F1	U10_F1	U16_F2	U16_F2	U17_F8
12	U15_F3	U12_F1	U12_F7	U14_F5	U9_F1	U12_F5	U12_F5	U16_F3	U17_F8	U15_F3
13	U8_F2	U11_F2	U15_F1	U12_F2	U13_F3	U16_F3	U12_F8	U8_F2	U10_F1	U12_F8
14	U10_F8	U12_F8	U8_F3	U9_F2	U11_F2	U12_F8	U12_F7	U14_F5	U14_F5	U14_F5
15	U11_F1	U16_F2	U9_F1	U8_F1	U9_F4	U10_F1	U12_F2	U17_F8	U8_F2	U8_F3
16	U13_F3	U10_F1	U14_F5	U10_F8	U8_F3	U17_F8	U13_F3	U9_F4	U8_F3	U12_F7
17	U10_F4	U13_F3	U8_F2	U15_F3	U10_F8	U16_F2	U9_F4	U12_F1	U12_F8	U16_F2
18	U12_F8	U17_F8	U12_F8	U10_F2	U9_F2	U9_F2	U16_F2	U9_F2	U10_F8	U9_F4
19	U12_F7	U12_F5	U13_F1	U12_F7	U15_F1	U8_F2	U8_F3	U12_F8	U9_F4	U16_F3
20	U12_F5	U8_F2	U17_F8	U16_F2	U15_F3	U12_F2	U9_F2	U12_F5	U12_F1	U8_F2
21	U12_F1	U16_F3	U9_F4	U10_F4	U8_F2	U9_F4	U16_F3	U11_F2	U12_F5	U10_F8
22	U16_F2	U10_F4	U15_F3	U12_F8	U8_F1	U12_F7	U8_F2	U10_F8	U9_F2	U9_F2
23	U9_F2	U12_F2	U11_F2	U8_F2	U17_F8	U8_F3	U17_F8	U8_F3	U11_F2	U10_F4
24	U9_F4	U12_F7	U9_F2	U8_F3	U10_F2	U11_F2	U10_F4	U10_F4	U10_F4	U13_F3
25	U10_F2	U10_F8	U13_F3	U17_F8	U16_F3	U10_F2	U10_F2	U10_F2	U10_F2	U12_F2
26	U11_F2	U10_F2	U16_F3	U16_F3	U16_F1	U10_F4	U11_F2	U12_F7	U12_F2	U10_F2
27	U12_F2	U8_F3	U16_F2	U13_F3	U16_F2	U10_F8	U10_F8	U12_F2	U12_F7	U11_F2

Rank	U8_F2	U9_F2	U10_F2	U11_F2	U12_F2	U16_F2
1	U16_F2	U11_F2	U12_F2	U10_F2	U10_F2	U10_F2
2	U10_F2	U9_F4	U11_F2	U9_F2	U12_F7	U8_F2
3	U11_F2	U12_F2	U16_F2	U12_F2	U11_F2	U11_F2
4	U12_F2	U9_F1	U10_F8	U16_F2	U16_F2	U12_F2
5	U8_F3	U10_F2	U10_F4	U8_F2	U9_F2	U9_F2
Facilitator's line						
6	U9_F2	U16_F2	U8_F2	U9_F4	U10_F4	U9_F4
7	U16_F3	U8_F2	U10_F1	U11_F1	U12_F1	U13_F3
8	U9_F4	U17_F8	U12_F7	U10_F4	U8_F2	U16_F3
9	U17_F8	U10_F8	U9_F2	U10_F8	U9_F4	U16_F1
10	U8_F1	U12_F8	U9_F4	U8_F3	U12_F5	U15_F3
11	U10_F4	U11_F1	U8_F3	U12_F7	U10_F8	U15_F1
12	U16_F1	U12_F7	U17_F8	U9_F1	U14_F5	U9_F1
13	U13_F3	U10_F4	U13_F3	U12_F8	U10_F1	U17_F8
14	U10_F8	U12_F5	U11_F1	U12_F5	U8_F3	U17_F1
15	U12_F7	U8_F3	U16_F3	U12_F1	U12_F8	U12_F7
16	U15_F1	U15_F3	U12_F5	U17_F8	U11_F1	U11_F1
17	U10_F1	U17_F1	U12_F8	U15_F3	U14_F1	U10_F4
18	U15_F3	U13_F1	U14_F5	U13_F3	U17_F8	U12_F8
19	U17_F1	U14_F5	U12_F1	U10_F1	U13_F3	U13_F1
20	U11_F1	U13_F3	U17_F1	U16_F3	U16_F3	U10_F8
21	U12_F5	U12_F1	U8_F1	U14_F5	U13_F1	U14_F1
22	U14_F5	U15_F1	U13_F1	U17_F1	U17_F1	U8_F3
23	U12_F1	U10_F1	U14_F1	U13_F1	U15_F3	U10_F1
24	U13_F1	U14_F1	U15_F3	U15_F1	U9_F1	U8_F1
25	U9_F1	U16_F3	U16_F1	U16_F1	U8_F1	U14_F5
26	U12_F8	U8_F1	U15_F1	U8_F1	U15_F1	U12_F5
27	U14_F1	U16_F1	U9_F1	U14_F1	U16_F1	U12_F1

Rank	U8_F3	U13_F3	U15_F3	U16_F3
1	U16_F3	U16_F3	U15_F1	U13_F3
2	U8_F1	U13_F1	U9_F1	U8_F3
3	U10_F8	U15_F3	U13_F3	U16_F1
Facilitator's line				
4	U13_F3	U8_F3	U16_F1	U15_F3
5	U17_F8	U16_F1	U16_F3	U8_F1
6	U8_F2	U16_F2	U13_F1	U16_F2
7	U12_F8	U14_F5	U14_F1	U8_F2
8	U12_F7	U15_F1	U8_F1	U17_F8
9	U11_F2	U12_F5	U17_F1	U12_F8
10	U12_F2	U8_F1	U16_F2	U13_F1
11	U10_F2	U10_F2	U17_F8	U15_F1
12	U14_F5	U12_F1	U8_F3	U17_F1
13	U15_F3	U8_F2	U9_F4	U10_F8
14	U17_F1	U17_F8	U14_F5	U14_F5
15	U12_F5	U12_F8	U12_F8	U12_F7
16	U9_F2	U14_F1	U11_F1	U10_F2
17	U10_F1	U10_F8	U11_F2	U10_F4
18	U12_F1	U11_F2	U9_F2	U11_F2
19	U10_F4	U9_F1	U8_F2	U12_F5
20	U16_F1	U10_F4	U10_F1	U14_F1
21	U16_F2	U9_F2	U12_F1	U9_F4
22	U14_F1	U12_F7	U12_F5	U12_F2
23	U11_F1	U17_F1	U12_F7	U10_F1
24	U9_F4	U12_F2	U10_F4	U9_F2
25	U13_F1	U10_F1	U10_F8	U11_F1
26	U15_F1	U11_F1	U12_F2	U12_F1
27	U9_F1	U9_F4	U10_F2	U9_F1

Rank	U9_F4	U10_F4
1	U9_F2	U10_F2
Facilitator's line		
2	U11_F2	U12_F7
3	U10_F4	U10_F8
4	U9_F1	U10_F1
5	U16_F2	U9_F4
6	U12_F7	U12_F2
7	U10_F2	U11_F2
8	U8_F2	U12_F5
9	U12_F2	U12_F1
10	U11_F1	U17_F8
11	U12_F5	U14_F5
12	U12_F8	U12_F8
13	U14_F5	U9_F2
14	U17_F8	U8_F2
15	U15_F3	U8_F3
16	U17_F1	U16_F2
17	U12_F1	U11_F1
18	U10_F8	U8_F1
19	U10_F1	U16_F3
20	U14_F1	U17_F1
21	U15_F1	U13_F3
22	U16_F3	U15_F3
23	U8_F3	U9_F1
24	U13_F1	U14_F1
25	U13_F3	U16_F1
26	U16_F1	U13_F1
27	U8_F1	U15_F1

Rank	U12_F5	U14_F5
1	U12_F1	U12_F5
Facilitator's line		
2	U14_F5	U14_F1
3	U12_F8	U8_F1
4	U12_F7	U13_F1
5	U17_F1	U9_F1
6	U10_F4	U13_F3
7	U12_F2	U12_F1
8	U14_F1	U12_F7
9	U11_F1	U12_F2
10	U10_F1	U12_F8
11	U9_F4	U10_F4
12	U11_F2	U11_F1
13	U13_F3	U9_F4
14	U13_F1	U17_F1
15	U9_F2	U16_F1
16	U8_F3	U8_F3
17	U10_F8	U15_F3
18	U17_F8	U10_F1
19	U9_F1	U16_F3
20	U10_F2	U15_F1
21	U8_F2	U9_F2
22	U16_F3	U10_F8
23	U15_F3	U17_F8
24	U8_F1	U11_F2
25	U15_F1	U8_F2
26	U16_F2	U16_F2
27	U16_F1	U10_F2

Rank	U12_F7
F's line	
1	U12_F2
2	U10_F4
3	U12_F1
4	U10_F2
5	U12_F5
6	U9_F4
7	U10_F8
8	U8_F3
9	U11_F2
10	U14_F5
11	U12_F8
12	U10_F1
13	U9_F2
14	U17_F8
15	U17_F1
16	U8_F2
17	U16_F2
18	U11_F1
19	U14_F1
20	U16_F3
21	U13_F3
22	U8_F1
23	U15_F3
24	U13_F1
25	U9_F1
26	U15_F1
27	U16_F1

Rank	U10_F8	U12_F8	U17_F8
1	U17_F8	U10_F8	U10_F8
2	U10_F1	U17_F8	U12_F8
Facilitator's line			
3	U10_F2	U12_F1	U8_F3
4	U12_F8	U12_F5	U16_F3
5	U10_F4	U8_F3	U9_F2
6	U8_F3	U12_F7	U8_F1
7	U12_F7	U14_F5	U17_F1
8	U11_F2	U12_F2	U16_F1
9	U12_F2	U9_F4	U10_F4
10	U9_F2	U11_F2	U8_F2
11	U8_F1	U17_F1	U10_F2
12	U11_F1	U9_F2	U15_F3
13	U8_F2	U10_F4	U9_F4
14	U12_F5	U9_F1	U12_F7
15	U16_F3	U14_F1	U16_F2
16	U9_F4	U16_F3	U13_F3
17	U13_F3	U15_F3	U11_F2
18	U17_F1	U13_F1	U12_F5
19	U12_F1	U13_F3	U10_F1
20	U16_F2	U10_F1	U13_F1
21	U14_F5	U16_F2	U15_F1
22	U16_F1	U11_F1	U9_F1
23	U15_F3	U8_F1	U12_F2
24	U15_F1	U15_F1	U14_F5
25	U13_F1	U10_F2	U12_F1
26	U14_F1	U16_F1	U11_F1
27	U9_F1	U8_F2	U14_F1

Table 2.4. Corpus 2 cluster analysis: distance table. 1000 most frequent word. Cosine delta distance. Texts are grouped by the facilitator shared; thus, the first 10 columns are occupied by those texts written with facilitator 1. Facilitators are cipher coded; users are alphabetically coded. Each row represents a rank position. Higher the rank, stylistically closer the texts. For example, considering U8_F1 in this table, its closest texts are U16_F1, U14_F1, U15_F1 and U8_F3. For U9_F1, U15_F1, U11_F1, U13_F1 and U16_F1 occupy the first four rank position. The thick red line (named Facilitator's line) represents the line above which we should expect to find just those texts that share the same facilitator expressed at the top of the column, according to the hypothesis that facilitators are the sole source of text production. For F1 it is positioned between position 9 and 10, as F1 assisted 10 different users. Texts coded in red refer to texts of the same user (of the one expressed by each column) that rank above the red line. In orange texts that belong to the same user that rank below the red line. 27 (words) and 28 (trigrams) texts are red coloured; therefore. they have broken the red line. 22 (words) and 23 (trigrams) texts are ranked in the first three rank position, indicating clear user-driven similarity. 8 users out of 10 has at least one text that classify in the top three rank position.

Texts of both different users and facilitators that appear below the red line, do not show a clear and unique pattern of interpretation. The unbalanced nature of the corpus does not allow for direct and exhaustive considerations of the different relationships that are consolidated in the corpus. For that, we would need a 10x10 corpus (10 users all assisted by 10 facilitators). However, we can observe some general patterns in terms of distance: inter-facilitator similarities (F1 appears similar to F3 and distant from F2), inter-user similarities (U8 is similar to U16, U9 to U11, U10 to U12, U11 to U9, U10 and U12; U12 to U14 and U10; U13 to U15 and U16; U14 to U12 and U13; U15 to U13, U9 and U16; U16 to U8, U15, and U13), and user to facilitator similarities (U8_F3 and U16_F3 to F8, U9_F4 to F2).

The rank analysis of texts clearly shows how often texts that either share the user or the facilitator occupy higher rank positions. To quantitatively reinforce the rank analysis results, we conducted a set of statistical analyses on the underlying distances between texts resulting from Stylo calculations. Distance values refer to the most frequent words analysis.

In order to statistically address the data, we differentiated five groups of distance values based on the relationships existing between texts. One group (IU) refers to the distance values between texts that share the same user. The second group (FU) refers to the distance values observed between texts that share the same facilitator and users who have stylistic similarities (see inter-user similarities in Study 1 and the cluster analysis in Study 2; inter-user similarities are also summarized in Table 2.5).

User	**User with Similar stylistic fingerprint**	
U8	U16	U14
U9	U11	
U10	U11	U12
U11	U10	U12
U12	U10	U11
U13	U14	U8
U14	U13	U8
U15	U16	
U16	U8	U14
U17	U8	U16

Table 2.5. Inter-user stylistic similarities. These relationships were extracted from the cluster analyses described in study 1 and study 2. Similarities with up to two users were assigned. As a result, some of the relationships are not mutual.

The third group (F) refers to distance values found between texts that share the facilitator, but the users do not have stylistic similarities. The fourth group (RU) includes texts that do not share the facilitator but have users with stylistic similarities. Finally, the fifth group (NR) contains texts that do not share facilitator or users with stylistic similarities. No more than two relationships were considered for each user. Table 2.6 below summarizes the different groups, the number of texts considered within each group and the mean distance value.

A first look at table 2.6 shows how the number of texts considered for each group is highly unbalanced. In particular, the group that does not acknowledge any relationship between texts (NR) represents more than half of the samples. Following the order in which the groups appear in table 2.6, note that the mean distance value increases as the co-operational effort within texts decreases. The more the stylistic fingerprint is shared (FU) the closer the texts are.

One sample T-test

	Nr of distance values	*Mean (SD)*	*μ1*	*Test result*	*p-value*	*μ2*	*Test result*	*p-value*
FU	33	0.79 (0.09)	1	1	0.0000	1.04	1	0.000
F	109	0.89 (0.12)	1	1	0.0000	1.04	1	0.000
IU	60	0.89 (0.10)	1	1	0.0000	1.04	1	0.000
RU	117	1.04 (0.07)	1	1	0.0000	1.04	0	0.371
NR	437	1.10 (0.08)	1	1	0.0000	1.04	1	0.000

μ1=neutral distance value
μ2 = average distance value

Table 2.6. One sample t-test. The t-test was run twice, with two different values for μ. The value of μ = 1 was chosen as a neutral distance value, since cosine delta distance can assume values between 0 and 2, with 0 referring to the highest level of similarity and 2 to highest level of distance. The value of μ = 1.04 was chosen in order to detect differences from the average of the observed distance values. Texts that share either the same user or the same facilitator have distance values significantly lower than both μ-values. FU refers to texts that share the same facilitator and users that have stylistic similarities (table 2.4). F refers to texts that share the same facilitator but no user with stylistic similarities. IU refers to texts that share the same user. RU refers to texts that just share user with stylistic similarities. NR refers to texts that do not share users or facilitators.

We first carried out a one-sample t-test to evaluate each group's divergence from an average (μ = 1,04) or neutral (μ = 1) distance score (Table 2.6). Results show that, on all occasions, groups differentiate from the neutral value (μ = 1). Groups FU, F and IU having lower values and groups RU and NR higher values. Similarly, the groups' distance values statistically differ from the average distance registered in the analysis. The only exception is represented by the group RU.

Next, we conducted paired t-tests to check whether the inter-group distances are statistically significant. In particular, we focused on the statistical comparison of group IU with all the other groups. To avoid the lack of balance in the number of textual distances for each group, the t-test was conducted with a sampled number of distance values and iterated 10 times. The analysis (displayed in table 2.7) shows that the registered distance values between the IU group and the others are statistically different (p <0.005) with the only exception being the distance values between texts that share the same user (IU) and texts that share just the same facilitator (F).

Finally, we used a supervised machine-learning analysis to investigate the number of texts that could be classified correctly according to their group.

Paired T-test (10-time iterated sampling)

Group 1	*mean*	*Group 2*	*mean*	*Test result*	*p value*
IU	0.89	**FU**	0.78	1	0.0000
IU	0.89	**F**	0.89	0	0.6281
IU	0.89	**RU**	1.04	1	0.0000
IU	0.89	**NR**	1.10	1	0.0000

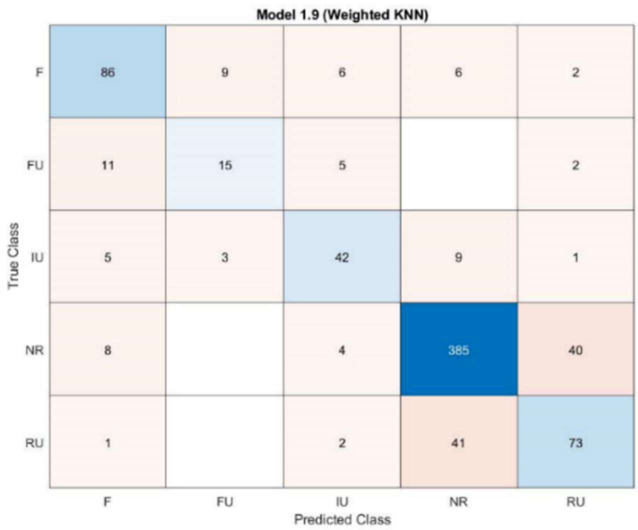
Table 2.7. Paired T-test (10-time iterated sampling). The mean distance between the IU group and the others is tested with Student's t-test). Given the unbalanced number of texts representing each group, the t-test was conducted with sampled values in order to equalize the number of observations for each group. Random sampling was conducted ten times. Then the t-test was repeated with each sample. The average p-value is reported: the registered differences in distance values are statistically significant, with the only exception being the differences between texts that share the same user (IU) and texts that just share the same facilitator (F).

The data were tested twice; first, with a weighted KNN algorithm (5-fold cross validation), then with an SVM algorithm (5-fold cross validation). The results are reported in figure 2.4 (I, II). The weighted KNN classification had a 79.49% accuracy and could assign texts distances to all the groups. The SVM classification had a lower accuracy score 65.21% and could assign texts just to 2 groups (F and NR). However, besides the accuracy score, it is worth noting the number of texts that share the same user being classified as texts that share the same facilitator (39 out of 60). A value very similar to that detected in the Bootstrap consensus network analysis (see study 2B below), and a higher value if we considered the rank analysis displayed in table 2.8, where just 27 texts were classified above the red line.

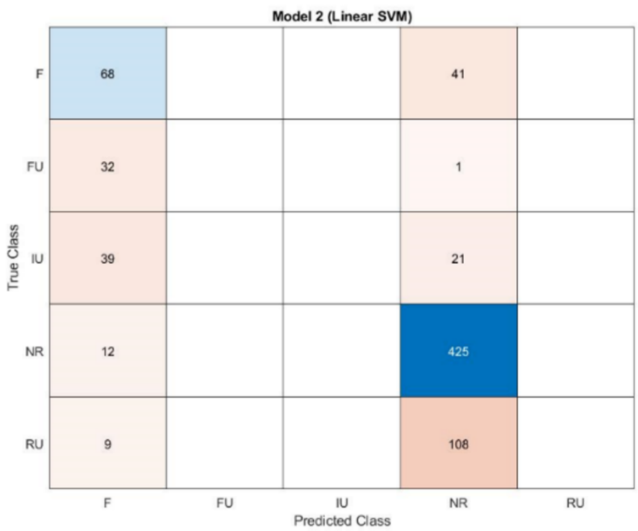
Overall, the statistical analyses conducted with the distance values confirm what was displayed by the rank analysis, namely that the style of texts is influenced either by the facilitator they share or by the user. Moreover, these analyses could positively acknowledge inter-user similarities, reinforcing the presence of user contribution to text creation. While considering these analyses, it should be noted that distance scores are strongly affected by the unbalanced nature of the corpus. The heavy representation of F1, for example (half of the words written in the corpus are assisted by F1), makes F1 the strongest stylistic force detectable in the corpus, impacting consistently even in the choice of the most frequent words and most frequent characters. In addition, the lack of balance in the sizes of texts written by users has an impact on the distance values, not in terms of absolute frequency of some words, but rather in the representativeness of certain words within smaller texts. Let's consider, as an example, the case of U14. He typed more than 64000 words with F1 and slightly less than 6000 words with F5. This size imbalance can impact considerably on the distance values between texts as the number of words shared by the two texts may be fewer than those shared by texts with a higher number of words.

Words	With FAC1			With Fac2			With FAC3			With FAC4			With FAC5			With FAC7			With FAC8		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
U8_F1				**U8_F2**	U16_F2	U9_F2	**U8_F3**	U16_F3	U15_F3												
U8_F2	**U8_F1**	U16_F1	U15_F1				**U8_F3**	U16_F3	U13_F3												
U8_F3	**U8_F1**	U17_F1	U10_F1	**U8_F2**	U11_F2	E12_F2															
U9_F1				**U9_F2**	U11_F2	U16_F2				**U9_F4**	U10_F4										
U9_F2	**U9_F1**	U11_F1	U17_F1							**U9_F4**	U10_F4										
U9_F4	**U9_F1**	U11_F1	U17_F1	**U9_F2**	U11_F2	U16_F2															
U10_F1				**U10_F2**	E12_F2	U8_F2				**U10_F4**	U9_F4								**U10_F8**	E12_F8	U17_F8
U10_F2	**U10_F1**	U11_F1	E12_F1							**U10_F4**	U9_F4								**U10_F8**	U17_F8	E12_F8
U10_F4	**U10_F1**	E12_F1	U11_F1	**U10_F2**	E12_F2	U11_F2													**U10_F8**	U17_F8	E12_F8
U10_F8	**U10_F1**	U8_F1	U11_F1	**U10_F2**	U11_F2	E12_F2				**U10_F4**	U9_F4										
U11_F1				**U11_F2**	E12_F2	U9_F2															
U11_F2	**U11_F1**	U9_F1	E12_F1																		
E12_F1				**E12_F2**	U11_F2	U9_F2							**E12_F5**	U14_F5		**E12_F7**			**E12_F8**	U10_F8	U17_F8
E12_F2	**E12_F1**	U10_F1	U11_F1										**E12_F5**	U14_F5		**E12_F7**			U10_F8	**E12_F8**	U17_F8
E12_F5	**E12_F1**	U14_F1	U11_F1	**E12_F2**	U9_F2	U10_F2										**E12_F7**			**E12_F8**	U10_F8	U17_F8
E12_F7	**E12_F1**	U10_F1	U17_F1	**E12_F2**	U10_F2	U11_F2							**E12_F5**	U14_F5					U10_F8	**E12_F8**	U17_F8
E12_F8	**E12_F1**	U17_F1	U9_F1	**E12_F2**	U11_F2	U9_F2							**E12_F5**	U14_F5		**E12_F7**					
U13_F1							**U13_F3**	U15_F3	U16_F3												
U13_F3	**U13_F1**	U16_F1	U15_F1																		
U14_F1													**U14_F5**	E12_F5							
U14_F5	**U14_F1**	U8_F1	U13_F1																		
U15_F1							**U15_F3**	U13_F3	U16_F3												
U15_F3	**U15_F1**	U9_F1	U16_F1																		
U16_F1				**U16_F2**	U8_F2	U9_F2	**U16_F3**	U15_F3	U13_F3												
U16_F2	**U16_F1**	U15_F1	U9_F1				U13_F3	**U16_F3**	U15_F3												
U16_F3	**U16_F1**	U8_F1	U13_F1	**U16_F2**	U8_F2	U10_F2															
U17_F1																			**U17_F8**	E12_F8	U10_F8
U17_F8	U8_F1	**U17_F1**	U16_F1																		

Table 2.8. Corpus 2 cluster analysis.: texts' rank positions according to the facilitator they share, in words analysis. For each user-facilitator pair, the first three rank positions of texts grouped by a shared facilitator are displayed. Let us consider U8_1; since U8 wrote with FAC2 and FAC3, the ranking order of texts written with FAC2 and FAC3 relative to U8_1 is reported. If no user contribution is expected, we should not find consistent ranking patterns. Texts coded in yellow refer to texts that belong to the same user. 60 texts out of 60 rank at least in second position. 56/60 texts classify in the first rank position.



I



II

Fig 2.4. Supervised machine learning analysis. I. Weighted KNN classification, 5-fold cross validation. Accuracy scores 79.49%. Values were assigned to all the five groups. 50 texts that share the same user (83%) are classified as either texts that share the same user or texts that share the same facilitator. F = texts that share the same user but no user with similar stylistic fingerprint. IU = texts that share the same user. FU = texts that share the same facilitator and user with stylistic fingerprint. RU = texts that share user with similar stylistic fingerprint. NR = texts that do not share any user nor facilitator. II. SVM classification, 5-fold cross validation. Accuracy scores 65.21%. Values were assigned to just two different groups. 39 texts that share the same user (65%) are classified as texts that share the same facilitator. F = texts that share the same user but no user with similar stylistic fingerprint. IU = texts that share the same user. FU = texts that share the same facilitator and user with stylistic fingerprint. RU = texts that share user with similar stylistic fingerprint. NR = texts that do not share any user nor facilitator.

2.4.3.2 Study 2B: Bootstrap consensus network analysis

The analysis with the bootstrap consensus network computes and graphically displays all the linkages existing between each text (Fig 2.5). The consensus network is composed of nodes (that represent each text candidate in the corpus) and undirected links. Two nodes are connected when they show stylistic similarities. The weight of this similarity is proportional to the thickness of the link in the graph. Stylistically similar texts have thicker linkages in the graph. Together with the graphical report of these relationships (Fig 2.5) the R package returns a hedge table where, for each node, undirected links and their weight are reported (see Table 2.9). As before, this table was investigated to address the hypothesis that facilitators are the sole contributors to the production of texts. The color coding is the same as the one adopted for the cluster analysis distance tables. A blue code is added to highlight texts that share neither the facilitator nor the user with the node.

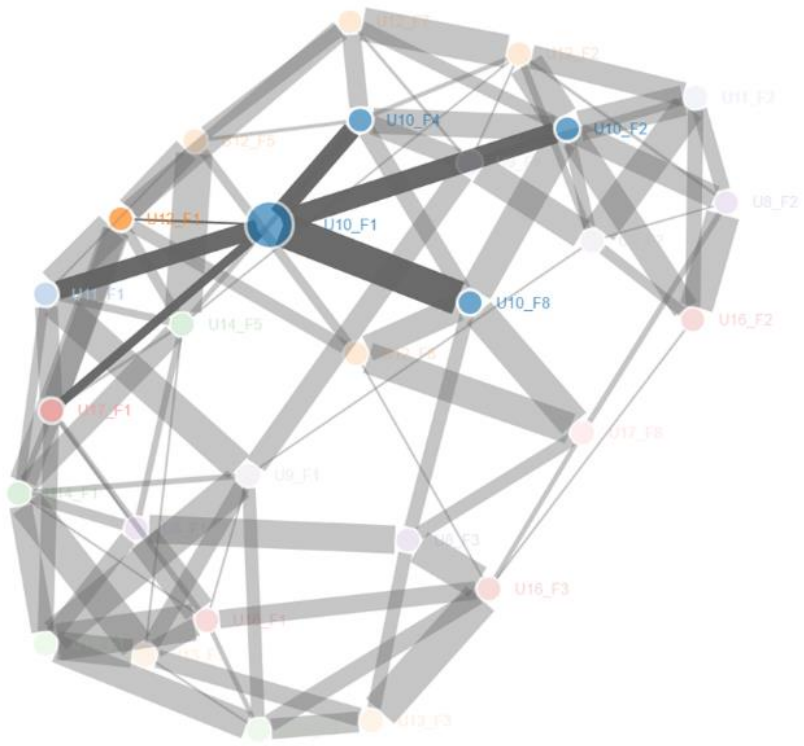


Fig 2.5. Bootstrap consensus network: graphical display. Nodes represents texts, linkage represents stylistic similarities between texts. The thickness of the linkage is directly proportional to the strength of the similarity. The more the linkage is thick the more the texts that it connects are similar. In the figure above the focus is on U10_F1 and its link with U10_F2, U10_F4, U10_F8, U11_F1, U11_F1 and U17_F1.

Rank	U8_F1		U9_F1		U10_F1		U11_F1		U12_F1		U13_F1		U14_F1		U15_F1		U16_F1		U17_F1	
1	U16_F1	224	U15_F1	249	U10_F8	247	U12_F1	258	U11_F1	258	U14_F1	256	U13_F1	256	U16_F1	291	U15_F1	291	U12_F1	112
2	U8_F3	170	U11_F1	217	U10_F2	93	U9_F1	217	U14_F1	159	U15_F1	172	U12_F1	159	U9_F1	249	U8_F1	224	U11_F1	108
3	U15_F1	63	U9_F4	105	U11_F1	74	U17_F1	108	U12_F5	153	U16_F1	75	U15_F1	112	U13_F1	172	U13_F1	75	U15_F1	51
4	U14_F1	25	U13_F1	61	U10_F4	71	U10_F1	74	U17_F1	112	U13_F3	73	U14_F5	95	U15_F3	168	U16_F3	71	U10_F1	17
5	U14_F5	9	U15_F3	38	U17_F1	17	U14_F1	18	U12_F7	95	U9_F1	61	U8_F1	25	U14_F1	112	U17_F1	7	U14_F1	8
6	U17_F1	2	U14_F1	7	U12_F1	1	U14_F5	13	U12_F8	36	U14_F5	1	U11_F1	18	U8_F1	63	U15_F3	5	U16_F1	7
7			U9_F2	1			U12_F5	1	U14_F5	23	U15_F3	1	U17_F1	8	U17_F1	51	U9_F1	1	U8_F1	2
8			U16_F1	1					U10_F1	1			U9_F1	7			U14_F1	1	U14_F5	2
9													U16_F1	1						
Facilitators' line																				

Rank	U8_F2		U9_F2		U10_F2		U11_F2		U12_F2		U16_F2	
1	U16_F2	240	U11_F2	240	U12_F2	277	U9_F2	240	U10_F2	277	U8_F2	240
2	U10_F2	115	U9_F4	185	U10_F8	219	U10_F2	201	U12_F7	239	U10_F2	154
3	U11_F2	47	U10_F2	30	U11_F2	201	U12_F2	121	U11_F2	121	U11_F2	50
4	U17_F8	7	U16_F2	23	U16_F2	154	U16_F2	50	U9_F2	11	U9_F2	23
5	U12_F2	2	U12_F2	11	U10_F4	139	U8_F2	47	U10_F4	4	U16_F3	1
Facilitators' line												
6	U9_F2	1	U8_F2	1	U8_F2	115	U9_F4	14	U8_F2	2		
7			U9_F1	1	U10_F1	93			U14_F5	1		
8					U12_F7	37			U9_F4	1		
9					U9_F2	30						
10					U9_F4	7						

Rank	U10_F8		U12_F8		U17_F8	
1	U10_F1	247	U17_F8	206	U10_F8	225
2	U17_F8	225	U10_F8	151	U12_F8	206
Facilitators' line						
3	U10_F2	219	U12_F1	36	U8_F3	39
4	U12_F8	151	U12_F5	19	U8_F2	7
5	U10_F4	66	U16_F3	1	U16_F3	5
6	U8_F3	42				

Rank	U8_F3		U13_F3		U15_F3		U16_F3	
1	U16_F3	250	U16_F3	300	U15_F1	168	U13_F3	300
2	U8_F1	170	U15_F3	91	U13_F3	91	U8_F3	250
3	U10_F8	42	U13_F1	73	U16_F3	68	U16_F1	71
Facilitators' line								
4	U17_F8	39	U8_F3	39	U9_F1	38	U15_F3	68
5	U13_F3	39			U16_F1	5	U17_F8	5
6					U13_F1	1	U12_F8	1
7							U16_F2	1

U12_F7	
F's line	
U12_F2	239
U12_F1	95
U10_F4	75
U12_F5	40
U10_F2	37
U9_F4	2

Rank	U9_F4		U10_F4	
1	U9_F2	185	U10_F2	139
Facilitators' line				
2	U9_F1	105	U9_F4	79
3	U10_F4	79	U12_F7	75
4	U11_F2	14	U10_F1	71
5	U10_F2	7	U10_F8	66
6	U12_F7	2	U14_F5	6
7	U12_F2	1	U12_F2	4
8			U12_F5	3

Rank	U12_F5		U14_F5	
1	U14_F5	287	U12_F5	287
Facilitators' line				
2	U12_F1	153	U14_F1	95
3	U12_F7	40	U12_F1	23
4	U12_F8	19	U11_F1	13
5	U10_F4	3	U8_F1	9
6	U11_F1	1	U10_F4	6
7			U17_F1	2
8			U13_F1	1
9			U12_F2	1

Table 2.9. Bootstrap consensus networks: undirected links and weight table. Range: 100 to 5000 most frequent words. The table represent for each text the links established with the other texts in the corpus and the strength of their relationship, also named weight. Texts are grouped by the facilitator shared; the red line indicate the limit above which we should find just texts written by the facilitator expressed by the column. Red code is used for those texts of the same user expressed by the columns that rank above the red line. As seen in table 2.4, the red line is given by the number of texts written with the same facilitator as the one expressed by the column. So, in the case of column U10_F1, U10_F8, U10_F2 and U10_F4 rank above the red line, respectively at 1st 2nd and 4th position. As for U10_F1 the red line is defined at position 10 all these texts are red coded. These ranks provide a meaningful hint of how texts written by U10 are inherently similar independently of the facilitator involved in the communication. Texts of the same user expressed by the column that rank below the red line are reported in orange. The orange coding is particularly meaningful for those facilitators (as F4, F5, F7 and F8) where the red line is particularly high placed (above the third rank position). 23 texts (out of 60) rank above the red line. 25 texts (out of 60) rank in the first three rank positions. 38 texts (out of 6o) rank in the first five rank positions.

Twenty-five texts rank above the red line, 23 texts classify in the first three positions and 38 in the first 5 positions. Thus, texts of the same user consistently occupy higher ranking positions than would be expected if users did not make a stylistic contribution, and very often they are in the closest neighbourhood of similarity. It should be also noted that of the 190 links recognized by the analysis, 100 out of a possible 140 are between texts that share the same facilitator. The count of 140 refers to the total number of possible combinations of links that can be established between texts written with the same facilitator. For example, since ten users wrote with F1, each text written with F1 can be linked, in theory, to nine other texts written with F1 (thus, 90 links can be established for F1), 30 for F2 (6 users with 5 links each), 12 for F3 (4 users with 3 links each), 2 for F4 and F5 (2 users with 1 link each), and 6 for F8 (3 users with 2 links each). Thus, 42 out of a possible 60 links are between texts that share the same user, and 48 out of a possible 554 links are between texts that share neither the facilitator nor the user. However, if the weight of each link is considered (the higher the weight, the closer the texts), then 96% of the weights of the links are saturated by user-to-user and facilitator-to-facilitator links (27% and 69%, respectively). Moreover, if we consider the average weight for each class (user-to-user, facilitator-to-facilitator, and user-to-facilitator) we see that relationships between texts of the same user, and between texts that share the same facilitator, have a similarly high weight average, while texts that do not share either the facilitator or the user have a lower weight average (see Table 2.10). Finally, it should be noted how even in the consensus network analysis inter-user similarities can be detected. Relationships are mostly created between the same array of users, independently of the facilitator involved in the communication process. U8 is linked across different facilitators to U16, and U10; U9 to U11 and U10; U10 to U12; U11 to U9, U12, and U10; U12 to U11, U14, and U10; U13 to U15, and U16; U14 to U13, and U12; U15 to U16, U9, and U13; U16 to U13, U8, and U15; U17 to U12, and U10. These links are consistent with the inter-user similarities found in the analysis of the distance tables (Fig 2.4).

	N° of links	**Total weight**	**Weight %**	**Average**
Same user	42	4571	27%	109
Same facilitator	100	11554	69%	115
Different U-F	48	674	4%	14

Table 2.10. Bootstrap consensus network: links and weight analysis. Statistic regarding links between texts of the same user, between texts written with the same facilitator and links between texts that shared nor the user nor the facilitator are reported. The number of links column counts for each group the number of existing relationships within the corpus. The total weight column indicates for each group the sum of the strength of each existing link. The weight percentage column reports for each group how much the weight strength impact on the analysis. The average column report for each group the average weight that characterizes links. While links between texts of the same user are fewer than all the other possible link, their weight account for the 27% of the total. The average weight existing between texts of the same user is quite similar to the one that exists between texts written with the same facilitator. Interestingly, this table shows that the bootstrap consensus network is able to detect similarities between texts that share the user or the facilitator.

2.4.4 Summary

This study was designed to test the assumption that FC users do not contribute stylistic characteristics to the texts they produce with the assistance of multiple facilitators. If this was the case, cluster analysis and bootstrap consensus network results would not show any grouping between texts of the same user, nor any pattern of similarity between texts of the same user. Cluster analysis results were not consistent with this assumption. The cluster analysis conducted on texts divided by user-facilitator pairs (Figs 2.3 I and II, tables 2.4 and 2.8) shows how relationships are detected mainly between texts that share either the user or the facilitator. This claim is also supported by the bootstrap consensus network analysis (Figs 2.4 and 2.5 and table 2.9) that shows that two major stylistic forces can be ascertained: that of the facilitator and that of the user. If facilitators were the only authors of texts, no significant similarities between texts of the same user across different facilitators should have been observed. Clearly, these results are not consistent with the starting assumption. Besides, there were also patterns of inter-user similarity, consistent with what was shown in Study 1. The existence of these similarities also refutes the starting hypothesis.

2.5 General discussion

The reported studies challenge the maximally sceptical starting position, namely that the facilitator is the sole agent to whom text written by FC users can be attributed. The results clearly show that texts written via FC generally present two linguistic imprints: the user and the facilitator. Based on this result, FC is better described as a co-creation process in which two distinct and active participants collaborate in the production of linguistic content. It is worth noting that this acknowledgement of dual linguistic imprints cannot fully account for the nuances of the text production dynamic of FC. The nature of the corpora and these methods do not allow us to discern the details of what originates with the user and the facilitator. The scope of these analyses is at the stylistic level with no presumption nor power to distinguish facilitators' traits from users' features on a sentence-by-sentence basis. Also, these analyses do not allow any comment on how the facilitator influences and supports the user. These questions require other methods and task-oriented analyses (we further develop in Chapter 3). What the present results clearly show is that the user is not linguistically passive, and the facilitator moulds rather than wholly constructs the typed text.

Acknowledging two stylistic forces in the production of FC text does not shed light on the nature of the contents expressed in the texts. Co-authorship does not offer certainty that a message written by integrating two linguistic sources fully mirrors the FC user's own intention. The existence of user-dependent similarities at the lexical level suggests, however, that users are actively involved in the selection of lexical forms, the linguistic components specifically deputed to convey meaning. This demonstrates the FC users' ability to transform semantic concepts into linguistic code, coherently within given syntactical and pragmatic contexts. This suggests that FC users possess a level of literacy skills, which any AAC intervention should seek to nurture and develop to improve users' quality of life.

It could be argued that an AAC technique that cultivates co-authorship may not foster the users' autonomy and independence. This issue of autonomy, alongside that of authorship, has often been central to the debate on the utility of FC. These two issues should be considered and addressed separately as they may reflect two different goals. This research addressed the issue of authorship and the possibilities of increasing the AAC users' communication options. The results clearly show that a technique like FC extends users' ability to express themselves linguistically. A co-authorship framework does not guarantee independence, which may reach different levels in the case of different users. These differences may originate in the users' inherent characteristics or in the stage of development in FC training. Over time, significant autonomy of expression may be achievable for some, but not for others. In both cases, however, using an AAC technique fostering co-authorship may provide developmental and quality of life advantages through increased communication options that might not otherwise become available.

Finally, it is important to consider the extent to which stylistic characteristics may be consciously or unconsciously modified or adapted in a collaborative setting such as FC. Stylometry and authorship attribution models are built on the general assumption that each person possesses a unique and unconscious stylistic fingerprint that can be detected and quantified through statistical procedures. This notion, first introduced by Lutoslawsky (1898) is widely held in the field of stylometry (Juola, 2008; Eder, 2015) as it has been proven valid in multiple authorship attributions. However, the possibility that authors can directly manipulate their own style for privacy or falsification has been addressed in recent times. For example, Brennan et al. (2012) showed how non-expert users can obfuscate their own stylistic fingerprint or imitate the one of a given model. To what extent the results provided in this chapter can be interpreted as the effect of facilitators' style imitation requires comment.

It could be argued that user-dependent stylistic similarities detected in Study 1 and 2, are nonetheless the results of facilitators modifying their style to render it more attributable to the FC user. All studies conducted so far on adversarial stylometry have dealt with conscious and deliberate style modification (Brennan et al., 2012). Suggesting that facilitators deliberately modify their own style to suit the user they are working with would imply that the facilitators' influence on the generated text is conscious. The sceptical position on this has been that the facilitators' influence is an unconscious ideomotor effect (Wegner et al., 2003; Saloviita, 2018). This contradiction must be addressed if an imitation hypothesis is adopted. Moreover, no studies have so far demonstrated the possibility of imitating more than one style simultaneously. This hypothesis, while logically possible, requires demonstration. Besides, even if we assume that facilitators consciously manipulate their style such that statistical models end up attributing texts to users instead, and also that facilitators can maintain up to ten different stylistic systems and use them in the correct contexts, we must contend with the issue of stylistic models. Style imitation research has always dealt with participants that deliberately conform their style to that of a model (Brennan et al., 2012; Daelemans, 2013; Emmery et al., 2021). However, in the case of FC, facilitators have no external models to which they can refer, so it is unclear on which basis they would organize their imitation. The users would have to have their own styles for the facilitator to imitate and mix with their own. It is unclear how these styles would become known to the facilitator if the users can only express themselves through collaboration with the facilitator in the first place.

It could still be argued that a model is created by the first or most consistent user-facilitator pairing. The first facilitator of each user may develop a style that obfuscates their own and has some unique and individual characteristics that individuate the user, as the results of Study 1 may suggest. Other facilitators who work with the user later might imitate the style developed by the first facilitator for that specific user. If this is how FC develops, we would expect that the imitation would reflect all the stylistic characteristics of the produced text, including those that are due to the facilitator. The results of Study 2 show that independent stylistic signatures are detectable for the facilitators and user. It is unclear how a later facilitator can purposely select user-dependent characteristics in their imitation, but leave out those of the original facilitator, especially at the level of word and character-trigram frequency. This would require discriminating patterns that are facilitator-dependent from those that are user-dependent, and only mixing the user-dependent ones with their own style. This would need to be done separately for every user with whom the facilitator works. It is highly unlikely that such stylistic imitation is feasible. A more likely, and certainly more parsimonious, explanation of the results obtained here is that both the facilitator and user contribute to the style of jointly produced text.

One possible dynamic underlying the observed co-authorship is that facilitators create syntactical structures within which users can fill in their own content. Whether this form of scaffolding occurs would need to be investigated using qualitative analysis. Syntactical scaffolding by the facilitator may also involve adjusting morphological endings, suggesting linkers or auxiliary verbs, or providing syntagmatic prompts to help begin communication (e.g, “I think that …”, or “I feel that …”). These prompting actions could be unique to each facilitator, which could lead to algorithms recognizing text with these expressions as authored by facilitators. In this respect, the facilitators’ work would be comparable to that of editors. As described in the case of Hildegard of Bingen (Kestemont et al., 2014), the editorial effort of adjusting sentences online (Hildegard could not write so she dictated her thoughts) can lead to algorithmic detection of the stylistic fingerprint of the editor, very much like the present results obtained for FC facilitators. It should also be noted that no redactional revision of the texts was performed. In fact, even in the choice of particular redactional forms can reside clues of someone's participation in the typing process. For example, the Italian word corresponding to /yes/ was used in the text in two alternative forms: the accented and correct one /sì/ and the clitic /si/, incorrect, though used habitually in colloquial writing. The use of the first version appears consistently throughout the texts written with F2, while the second one among the same users when writing with F1. Although no change in meaning is conveyed by choosing alternate one of the two forms, this facilitator-dependent discrepancy contributes to enhancing the distance between texts of the same user and in approaching texts that share the same facilitator. Given the modality of data collecting that -followed a retrospective approach (since it facilitated the collection of texts of greater size), there was no chance of deciding whether these redactional differences originated from the natural flow of FC dynamics, and therefore the facilitator's direct influence, or rather were the result of an explicit, post-hoc corrective intervention from the facilitator. This aspect represents a limitation of the methodology, so future studies should consider controlling possible external redactional interventions, being cautious to not interfere with the natural dynamic of FC.

If the presented evidence of FC users' stylistic contribution is accepted, consideration shifts to the utility of an AAC technique that may enable the user to co-author texts with trained facilitators. Clearly, a technique that, in due course, leads demonstrably to independent text production ought to be preferred over one that involves dependence on the assistance of a trained facilitator who also co-authors the user's texts. The issue of assisted communication only arises, however, in the context of significant sensorimotor and cognitive disabilities. Depending on the level of these disabilities, developing towards autonomous linguistic expression may not be a feasible goal. What must be judged in such cases is the potential utility of providing the individual with an effective means of text co-production that may not ever result in autonomy. The present results clearly demonstrate that the latter option does result in the individual producing a personal linguistic signature, even though this happens only with the availability of co-productive assistance. Given the limited prospects of these individuals conducting any aspects of their lives autonomously, and their expected dependence on others' care for the rest of their lives, we submit that co-creating text using a technique such as FC is very likely to be a developmentally and psychologically valuable exercise.

2. 6 Limitations and future directions

There are several limitations to the work reported in this chapter, and these are mostly inherent in the corpus of text that was produced over an extended period of time (>10 years in some cases) and was not designed in any way for the requirements of research. First, the available corpus is inherently unbalanced in the number of words representing each user and facilitator, and in the user-facilitator pairings. For instance, some users in the corpus have written consistently with five different facilitators while some others with just two. As we have noted, an effect of this imbalance is that some stylistic fingerprints, particularly those of the most prolific facilitators, are more consistently represented than others. Controlled corpus construction would aim for a more homogeneous assortment of user-facilitator pairs, with all users sharing the same set of facilitators, and writing a similar number of words in each user-facilitator pair. Such a controlled corpus comparable in size to the one analyzed here would require many years to accumulate.

Second, adopting a historical corpus precluded any control over the production of textual content. It was not possible to ascertain direct or indirect redactional interventions that could have affected the strength of textual similarities. It was also impossible to control the topics that were addressed in the generated text. On one hand, the text analysed is thereby free of the demand characteristics of a research study, but on the other, linguistic analysis is impacted by the divergence of topics chosen by facilitators or users, leading to uncontrolled differences in lexical targets.
A third limitation arises from the heterogeneity of cognitive and sensorimotor function among the users represented in the corpus, and the differences in their age, DD diagnosis, levels of facilitation, and the period of FC use. In addition, it was not possible to collect information about the level of the users' language comprehension or literacy. Thus, the only confirmed commonalities among the users were their adoption of FC and the facilitators they had shared.

Finally, despite the long periods over which the corpus was produced, the present methods did not allow us to look for a developmental trajectory in the users' stylometric contributions to their texts. Future studies should aim to investigate whether the user's stylistic fingerprint changes strength with increased experience with FC, and if so, which conditions of training or practice best facilitate this.

2.7 Conclusion

The studies presented in this chapter analysed a large corpus of FC text produced over a number of years to test the hypothesis that only the facilitator's stylistic signature should be detectable in the text. This hypothesis follows from the view that the facilitator is the sole author of FC text. The results do not support this hypothesis as the user's stylistic fingerprint is detectable alongside those of facilitators. The conclusion is that FC text should be viewed as co-authored by the user and the facilitator. As the user is clearly a participant in text generation, there is scope for touch-based assistance to serve as a scaffold in DD individuals' linguistic development, and to contribute positively to their quality of life and connection with carers. Whether the individual does, or could develop to, generate typed text independently should not determine the value of practicing and better understanding touch-assisted typing techniques. Future work on these techniques should instead establish a developmental context within which research focuses on how best to utilize these techniques to enhance DD individuals' education and well-being. Such an approach would recognize the full significance of this chapter's findings. Just as the present analysis has shown that the FC user is not a passive recipient of ideomotor suggestion, it has also shown that the facilitator actively shapes the text that is typed. The level of facilitator contribution we have reported advises us that, in the proposed developmental approach, uses of FC texts should always be informed by the co-creative nature of the process.

In the next chapter, the linguistic contribution of users to the FC dynamic will be further addressed, within a closer perspective. In this chapter, users' contribution was examined as a function of frequencies in lexical and morphological choices out of large corpora of text productions. In chapter 3 we seek to address the contribution of users by looking closely at each single and sequential typing gesture.

CHAPTER 3: ARE USERS WITH DEVELOPMENTAL DISABILITIES LINGUISTICALLY INVOLVED DURING TOUCH-ASSISTED TYPING: AN ANALYSIS OF ARM AND EYE MOVEMENT PATTERNS IN FACILITATED COMMUNICATION.

3.1 Introduction

In Chapter 2, we have applied stylometric and machine-learning analyses to the largest available FC text corpus to show that the FC users' stylistic signature is detectable alongside their facilitators', both when multiple users write with the same facilitator and when the same user writes with multiple facilitators. We have proposed that techniques such as FC should be viewed as collaborative, co-productive processes, and valued for their contribution to users' development without making this conditional upon the achievement of autonomy. In this chapter, we report behavioural analyses of user-facilitator interaction during FC text production. In particular, we study the level of users' engagement and participation in the typing task.

The user-facilitator interaction may include three types of user involvement – motor, linguistic and communicative. The user's motor participation requires that they initiate and execute the typing gesture. Linguistic involvement requires the user to be involved in the production of word forms or completion of character strings (beyond being in control of the motor component). Both motor and linguistic involvement are necessary (but not sufficient) for the user's communicative involvement, which is the conveying of the users' communicative intentions through the typed words.

Based on these types of involvement, we can formulate four possible levels of user contribution in FC. The first level is that the user is inactive in terms of motor control, linguistic production, and communication. In this case, the facilitator carries the user's passive arm from key to key, each letter chosen entirely by the facilitator. No current view of FC proposes this. The second level is that the user participates in planning and executing the motor gestures towards the keys but does not control the linguistic choices being made. This is the ideomotor hypothesis whereby the typed words are the by-product of an unconscious, progressive, touch-delivered cueing from the facilitator to the user's arm-gesture towards the keyboard. Some studies have investigated how this phenomenon might arise from the user-facilitator interaction. Wegner et al. (2003) showed that it is possible to unconsciously answer questions on behalf of another person and project the answer's authorship on the other person. This is the pattern that has been suggested for the facilitator's participation in FC interaction, where the linguistic content produced by the facilitator is attributed and projected to the user by the facilitator themselves. However, Wegner et al. did not provide an exact representation of FC: first, they described what happens during a binary choice and not during a typing task (which is rather a >20-option choice), and second, they pre-emptively assumed that the user was not making any contribution to what was typed. Thus, while they demonstrated that it is possible to project the agency of our own motor and cognitive actions, their study did not faithfully replicate what happens during an FC session. Kezuka (1997) showed how the facilitator provides progressive and discrete (yes/no) cues as the user scans the keyboard with their index finger. Therefore, if at the start of the word "hello" the scanning is going from the key "L" in the direction of "A" (right to left), the facilitator provides some cues (exerting a counterforce) when the finger has passed the key "H", suggesting to the user to go back. The more the applied force, the more the finger should go back. Kezuka (1997) noted that this technique differs from prototypical FC, but the mechanism can be intuitively extended to most variations of FC.

Evidence that the user actively initiates the movement towards the keys is presented in Faure et al's accelerometery analysis (Faure et al., 2021). According to this account, we should expect the user to look in advance at the to-be-typed key. Since the motor component of the typing gesture is controlled by the user, we should expect an eye-hand coordination by the user and a gaze-anticipation of the key to be struck (as already described in Grayson et al., (2012) and Jaswal, (2020) although with a different technique often associated with FC). Eye-behaviour should reflect the finger's keyboard scanning while sensing for touch-generated cues, with eye-fixations migrating from one key to another before stopping on the correct one. In summary, at the second level of user involvement (the ideomotor perspective), the user's movement is voluntary (self-generated) as the facilitator is not carrying or driving the arm of a passive user, but just providing cues about the direction the arm has to follow. The user is therefore acting like an antenna sensing change in the facilitator's touch and changing the direction of movement accordingly. The cueing should happen progressively to the finger's position with respect to the keyboard. The information provided through touch should deliver binary information sequentially (left/right, stop/go, up/down) rather than providing immediate, detailed information about the to-be-pressed key.

In the third level of involvement, users may be in control not only of the motor process but also some of the linguistic components of the typing task. Quantitative analyses of texts produced via FC have shown that the writing style of FC users has some idiosyncratic and language-independent characteristics in lexical choices and syntactical structures that are different from their facilitators' own style (Tuzzi, 2009; Bernardi and Tuzzi, 2011a). Furthermore, as we have also shown in chapter 2, the stylistic fingerprint of users can be detected alongside that of facilitators in texts of the same user when assisted by different facilitators. In view of these results, we proposed an interpretation of FC as a co-creative process where both the users and facilitators cooperate in the construction of the linguistic output. We proposed that the facilitator may contribute to the scaffolding of the message with the user participating through lexical choices. This position does not exclude facilitators' contribution to text generation (their stylistic traits are detectable, see chapter 2), but it leaves room for the user to play an active role in the generation of linguistic content. Being involved in this way requires the user to possess literacy skills and to be able, at least, to match lexical choices to the context.

Finally, in a fourth level of involvement, the user participates in the motor, linguistic and communicative aspects of the task, therefore being in substantial control of the messages produced. So far, FC users' communicative involvement has been studied mostly using the message-passing task in which the user attempts to type content of which the facilitator is unaware or misinformed (Wehrenfennig et al., 2008; Schlosser et al., 2014). Generally, the proportion of such messages passed is quite low, although present in the literature (Wehrenfennig et al., 2008; Saloviita et al., 2014; Schlosser et al., 2014). It is a matter of debate whether the controlled message-passing task actually addresses the user's communicative involvement. As the messages to be passed are not connected to the users' own communicative intent, the task is essentially a game that tests the users' willingness to play, their ability to maintain non-intended content in working memory and their willingness to apply themselves to typing this out when required. It can be said that message-passing tasks at least test the user's linguistic involvement (which is a prerequisite for communicative involvement).

3.2 The present study

The present study's aim was to investigate whether FC users are involved beyond the second, motor level. We adopted a dual approach to achieve this. First, in Study 1, we analysed arm and eye movement data to seek indicators of facilitators' cueing. If user involvement only reaches up to the second level (ideomotor phenomena), we hypothesized that the facilitator must guide the user with a sequence of binary cues (left-right, up-down). If so, we should see a high level of directional indecision in the effector's (i.e., typing finger's) trajectory and a wandering pattern of visual exploration of the keyboard. This would mean that the final destination of the movement would not be as easy to identify at earlier points along the trajectory as it would be for a movement that was aimed directly at the target and not sequentially cued.

To address this hypothesis, we set up three tests. In Test 1, we derived a pointing movement profile from the pointing arm's position data. This profile was then compared to the eye-movement trajectory to study the extent to which the eye's movement to the vicinity of the target key leads or trails the typing finger's progress. We also compared each movement's profile to the trajectory predicted by a machine-learning (ML) classifier algorithm trained on the movement dataset. The purpose of this comparison was to test the degree of users' aiming indecision with respect to the target (through its effect on the predictability of the trajectory). In Test 2, we derived an index of tortuosity from hand position data to study the extent to which the trajectory contained deviations from smooth approach to the target key. In Test 3, we derived an index of eye-movement variability to study the extent of the eye-movement trajectory deviations and final aiming hesitation resulting from sequential cueing.

In Study 2, we hypothesized that, if the user was not actively engaged in producing the linguistic content, the data should reveal no signs of linguistic anticipation. In Test 1, we investigated the relationship between finger-to-keyboard distance and the arrival of visual fixation on the target. The purpose was to see whether users anticipated the next key to be pressed rather than visually following the finger to the target key. In Test 2, we investigated whether users showed signs of contextual linguistic facilitation. According to the ideomotor hypothesis, the movement to press a key that is highly probable given the preceding string of characters should not differ from the movement to type a low probability key. If this was not the case, then some level of the user's linguistic involvement would be implicated. To put it another way, if users were not engaged linguistically (and therefore not active in deciding which key to type next), approaching a character that was very probable given the context should not differ from approaching a low probability character. To test this, we calculated and analysed pointing speed and the precision and trajectory of visual fixations in the context of the to-be-typed character's probability.

3.3 Study 1

3.3.1 Test 1

If users are sequentially cued in the manner suggested by the ideomotor perspective, their pointing and eye movement trajectories should show signs of sensing and responding to facilitators' sequential cueing. Accordingly, we tested whether FC users' movement patterns revealed signs of such sensing for cues. Based on Kezuka (1997), we assumed that the facilitator's cueing would be in the form of a discrete sequence conveying binary direction information. If so, the user's movement trajectory should show signs of hesitancy and indecision because the cued user should only become aware of the target's position on the keyboard in the final stages of the pointing gesture. Pointing gestures are thought to be composed of an initial ballistic phase followed by a closed loop one (Meyer et al., 1988). The former covers most of the distance to the target, while the latter contains the fine control that enables precise approach to the target. If the facilitator provides the directional cueing that identifies the target key, we should expect the closed loop phase to contain multiple corrective sub-movements.

In Figure 3.1, the schematic movement profiles display the distance of the effector from the endpoint target in a standardized time framework. Each profile shows distance information for a pointing movement (from the completion of the previously typed key at T = -10 to the moment the next key is struck at T = 0). As a convention, we define the beginning of the forward phase of the movement as the instant where the arm is the furthest from the keyboard, having withdrawn following the previous keystroke. (Please see the Appendix II – Movement Analysis). The eye-tracking profile computes the eye-fixation distance from the target key in relation to the effector-to-keyboard distance. Finally, the ML profile (black line) displays the distance between the target key and the key the user is predicted to strike (by a machine-learning algorithm trained on the full corpus of movement data). Similarly to the eye-tracking profile, the ML profile is plotted in relation to the effector-to-keyboard distance (See Appendix II: Movement Analysis, Appendix III: Eye-Tracking, Appendix IV: Machine Learning for detailed information about data processing).

If the user is linguistically involved, and makes a movement to a known target, the trajectory should be smooth and fast (Figure 3.1a). The movement profile should be more symmetrical between the backward (lifting away from the keyboard) and forward (approaching the target) phases of the movement. The approach should not show abrupt slowing or an elongated section with the articulator close to the target key. The distance between the actual destination key and the one predicted by the ML classifier should mirror the movement profile, reducing consistently as the pointing finger's distance from the keyboard reduces. Accordingly, the eye-fixation distance from the target should rapidly drop once the movement starts as the finger's movement follows eye-fixation movement.

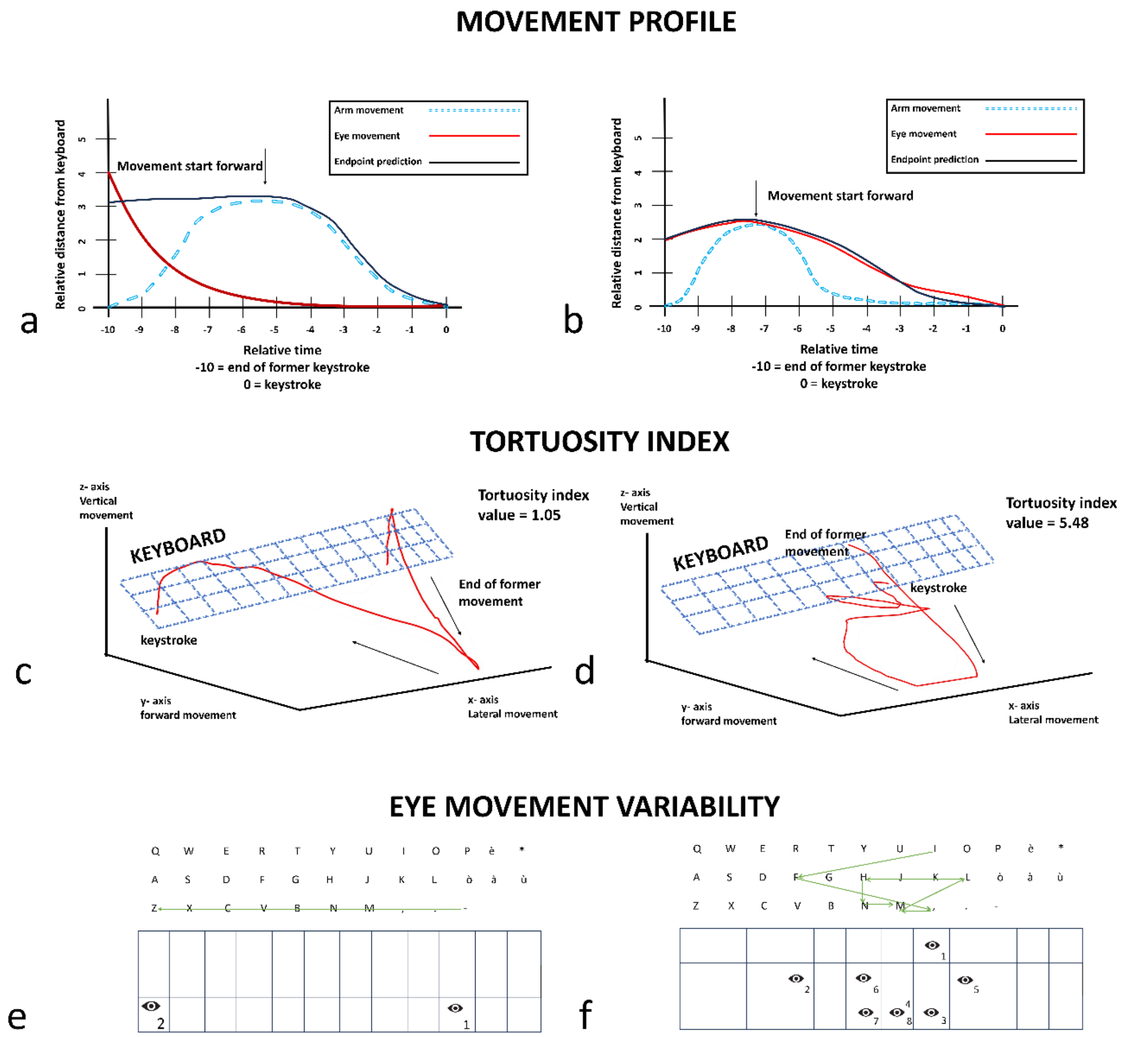


Fig. 3.1. Schematic comparison of expected trajectories for voluntary movements (a, c, e) and movements directed by the facilitator (b, d, f). a, b: pointing, eye-tracking and machine learning profiles (Study 1, Test 1). Schematic effector movement (blue), eye movement (red) and ML classifier

prediction (black) profiles of voluntary (a) and cued (b) pointing gestures. The horizontal axis depicts 10 sub-divisions of the time between the previous (t =-10) and current (t=0) keystrokes. The vertical axis depicts the effector's initial movement away from the keyboard after the previous keystroke (the positive-going part of the blue curve), followed by the movement towards the next keystroke (the negative-going part indicating diminishing distance from the keyboard). If the user is aware of the key to be pressed from early on in the movement (a), the distance between their eye-fixation and the target key should diminish early. Conversely, if the user discovers which key is next through successive facilitator cues (b), their eye-fixation should approach the target more gradually. With respect to the distance between the actual and ML classifier-predicted key, if the user is controlling the direction of the movement (a) the distance of the predicted key from the actual key should be proportional to the distance of the arm from the keyboard. On the other hand, if the user senses and repeatedly responds to the facilitator's cues (b), greater distances between the predicted key and the pressed key are expected even when the articulator's position is close to the keyboard. c, d: 3D illustrations of two pointing gestures with different tortuosity index values (Study 1, Test 2). c: the movement is steady and direct (tortuosity index value close to 1), d: the movement is high in tortuosity (index value above 5). e, f: Eye-movement variability (Study 1, Test 3). The sequence of visually fixated keys during a pointing gesture. e: gaze moves smoothly and directly to the target key without repeated direction changes due to cueing; f: eye fixates on different keys over the course of a high tortuosity effector-trajectory while responding to multiple directional cues from the facilitator.

3.3.1.1 Participants

Thirteen FC users (9 males, 4 females), aged between 15 and 30, participated in this data collection, together with six different facilitators. Each participant had a severe impairment of oral language preventing them from communicating verbally. The participants' recruitment took place between December 20th, 2015, and May 7th, 2016. A written invitation to participate in this study was circulated in the "Vi Comunico Che Penso" network of FC users and their families in Italy. "Vi Comunico Che Penso" is a charitable organisation involved in teaching FC and supporting the families of FC users. The invitees were members of the association and had used FC for a number of years and worked with multiple facilitators affiliated with the association. Two members of the research team were also members of the association and were known to the participants and their families in that capacity before the study was announced. The potential participants and their families received a written summary of the nature and scope of the study. Based on this information, the FC users and their caregivers gave written informed consent and agreed to travel from Italy to Nottingham, UK, to participate in data collection at the Human Movement Laboratory of Nottingham Trent University. The participants and their caregivers attended the sessions together and the caregivers were present throughout the data collection process. The task instructions and debriefing information were also provided to both the participants and their caregivers. Throughout each data collection session, the participants or their caregivers could call for rest periods or the end of the session. Ethical approval for the study was granted by the Nottingham Trent University College of Business, Law and Social Sciences Research Ethics Committee (N. 2016/101).

The table below (see Table 3.1) summarizes the users' principal information. The levels of facilitation refer to where on the user's body the facilitator places their dominant hand during the FC process.

Participant	Diagnosis	Age	Year of FC use	Level of facilitation
P1	Autism	21	>10	Elbow
P2	Dyspraxia of speech	16	>5	Elbow
P3	Williams Syndrome	23	>10	Shoulder
P4	Fragile-X syndrome	29	>10	Neck
P5 (F)	Cerebral Palsy	30	>10	Elbow/hand
P6	Autism	24	>10	Elbow
P7	Autism	20	>10	Elbow
P8	Developmental Coordination Disorder	22	>10	Elbow
P9	Autism	23	>10	Elbow
P10 (F)	Autism	24	>10	Elbow
P11 (F)	Down Syndrome	25	>10	Shoulder
P12	Down Syndrome	26	>10	Elbow
P13 (F)	Down Syndrome	24	>10	Elbow

Table 3.1. Participants presentation. The table summarize for each participant, their diagnosis, their age at the time they participated in the data collection, the years of expertise with the FC technique and their level of facilitation. The level of facilitation refers to the position the facilitator is holding or touching the user.

3.3.1.2 Procedure

The data were collected over a two-year period (July 2016-May 2018) in the Human Movement Laboratory at Nottingham Trent University, UK. Each user-facilitator pair participated at least four different rounds divided into two sessions: a normal session of Facilitated Communication with eye-tracking glasses, EMG and movement analysis, and an assessment of linguistic and mathematical ability via EMG and eye-tracking.

An 80cm x 100cm x 80cm desk was situated in the centre of the room, with the monitor and a keyboard on it. Two chairs were positioned in front of the desk, one for the user and the other for the facilitator. A left-side camera was set up to record, for each session, the user-facilitator pair, the keyboard and the monitor, and a front/rear camera to record the user-facilitator pair, this time focusing on the type and level of facilitation. Both the facilitator and the user wore SMI Eye-tracking Glasses (Copenhagen, DK). One Delsys Trigno (Natick, MA) surface EMG sensor was placed on the deltoid of the user's dominant arm, and another was placed on the deltoid of the facilitator's arm (whichever was used during facilitation). A four-unit Codamotion CX1 array (Rothley, Leics, UK) was used to track the user and facilitator's dominant wrist using active markers was used to record position data. A typing timer software (keylogger) was set-up to get the timestamp of each keyboard stroke. Users and facilitators sat in front of the computer and typed spontaneously about self-originated topics or answered some questions posed by the facilitator or the examiner. The two video cameras were set to register rthe whole setting. Participants were asked to perform the task for 6-7 minutes. Then the task was interrupted to allow the equipment to store the acquired data. (Please refer to Appendix I, Data acquisition for further information on how data were acquired and processed).

3.3.1.3 Methods

From the acquired data streams (see Appendix I, data acquisition), the movement profiles of each user's pointing gesture and the average profile of arm movement, eye-tracking distance from the target key and the distance between the ML-predicted key from the target key were plotted in a graph for each user. Then, the plotted profiles were compared to the schematic movement profiles displayed in 1a and 1b.

For the pointing movements, we calculated Euclidean distance between the effector and the target key. Timing information was then standardised (in terms of the proportion of each complete movement) to allow a direct comparison of all movements. By convention, a pointing gesture included the movements between two consecutive keystrokes. Thus, each gesture started with a return phase (the effector retreating from the keyboard following the previous keystroke) and a forward phase (the effector approaching the next target key). The forward phase was taken to start once the effector had reached its maximum distance from the keyboard. The pointing movement profiles for each participant were then averaged to determine their average profile.

The eye-tracking data were first coded manually for fixations with respect to the keyboard. The data stream was then segmented with respect to the timeframe of each pointing gesture so as to capture all the fixation coordinates during each pointing gesture. We then calculated the fixated key's distance from the target key. This enabled the generation of a fixated-to-target-key-distance profile for each pointing gesture. Finally, all these distance profiles were averaged for all keystrokes and plotted.

The machine-learning algorithm compared each individual movement to the trajectory predicted by a classifier algorithm trained on the entire movement dataset. The purpose of this comparison was to test the degree of users' aiming indecision with respect to the target. The ML classifier was used to assess the extent to which the destination key could be predicted while the movement trajectory progressed. The classifier was trained to predict the position coordinates along the movement trajectories based on the respective destinations on the keyboard. This classifier was then used to test each pointing movement alone and predict, at each timepoint, which key the movement was expected to hit. As a result, it was possible to plot at each timepoint of each pointing gesture, the distance between the key the movement was expected to hit, and the target key it actually hit. The distance profiles for each pointing gesture were then averaged over each participant's gesture set. The resulting profile was finally plotted against the actual distance of the effector from the target key.

Please refer to Appendix II - Arm movement analysis, Appendix III - Eye tracking Analysis and Appendix IV - Machine Learning, Appendix V – Key to key distance computation and Appendix VI - Data Summary for further information.

3.3.1.4 Results

The movement profiles of each participant are displayed in Figure 3.2. The dashed blue lines refer to each movement profile, intended as the interval between two keystrokes. At T = -10 the participant is concluding the former pointing gesture, at T = 0 the participant is striking the key. The thicker green line represents the average profile computed from all the pointing gestures.

Red lines refer to the distance between the visually fixated key and the target key. Black lines refer to the distance between the key the movement is expected to hit and the target key.

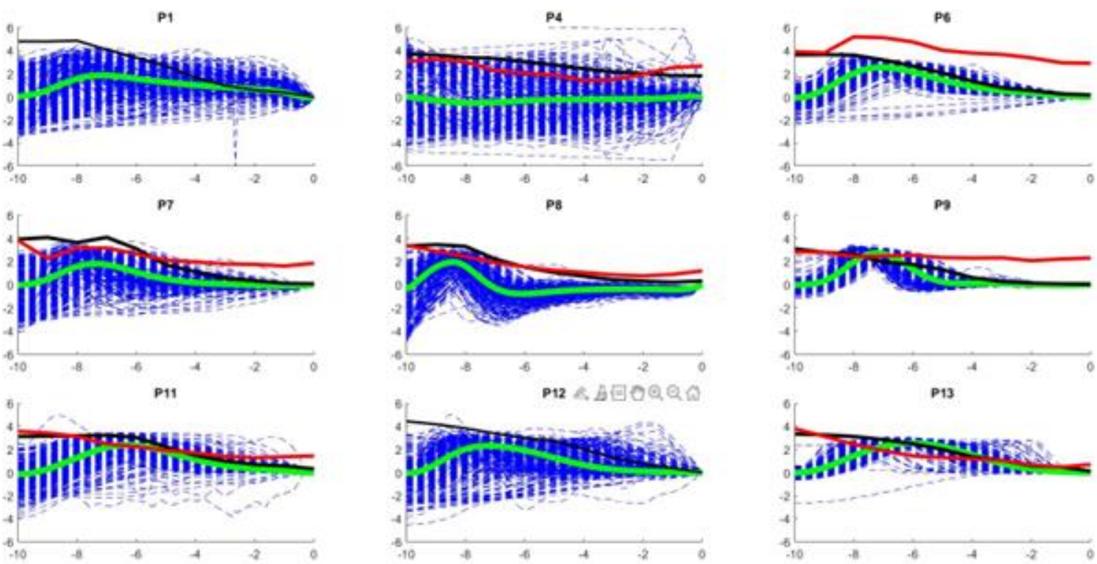


Fig. 3.2. Movement profiles. The movement profiles (dashed blue), the average pointing profile (green), the average distance between the predicted key and the target key (black), and the average distance between the fixated key and the target key (red) are shown for each participant. The axis conventions are the same as in Figure 3.1, with movement time and distance standardized as proportions for comparison across movements to and from different keys. No eye-tracking data were available for P1.

From the clusters of individual movement trajectories (blue), it is possible to note participants' variability, with P6, P8, P9 and P13 showing a more consistent pattern compared to the more variable patterns of P1, P4, P7, P12 and P11. With regard to average pointing behaviour (green), some users (P6, P11 and P13) show a steadier, more linear approach to the keyboard than others (P8 and P9) who show a more rapid decrease in the finger-to-keyboard distance and a long tail with the finger very close to the keyboard. Also, note that the return gesture (i.e., the movement of the user's hand from the keyboard to their own body in between each keystroke, represented by the positive-going part of the curve) is clear in all users except P4. The distance between the eye-fixation location and the target key (red line) decreases alongside and proportionally to the finger's distance from the target. Eye-tracking measurement was considerably affected by the difficulties of calibration during data collection. Nonetheless, they reinforce the expectation that participants' fixations hit the neighbourhood of the target key at some point. It is interesting to note that the trajectories of the ML classifier's prediction error and the finger-to-keyboard distance almost match for P6, P11 and P13 - prediction error declines (i.e., the final destination becomes more predictable) as the movement progresses towards the target. For the other participants, the prediction error decreases slower than the finger's distance from the target, with the final destination of the movement remaining less predictable even when the finger gets close to the keyboard. It is important to note one inter-participant difference in terms of movement profiles. Looking at the average profile, each user presents an individual and unique pattern of movement even in those cases where the users share the same facilitator (P7 and P8; P9 and P13; P11 and P12). All users (except P4) present a pattern of moving away from the keyboard (towards their chest) after the previous keystroke before initiating the approach to the next key. This is expressed by the bell-shape of the movement profile, with peaks representing the greatest distances from the keyboard. P4, however, does not exhibit this return gesture, showing a key-to-key pattern of movement rather than a key-resting position-key motion. Higher variability in the movement profile may represent a mixed pattern between key-to-key and key-resting position-key variants. Some users (P6, P8, P9 and P13) in fact present very little variability between different pointing gestures (blue lines create a compact and clear shape). Others, instead, present higher variability and a less discernible shape across the blue lines (P7 and P11). These patterns of movement belong to each user-facilitator pair's natural approach to FC. At no time during the data collection were the users asked to adopt a return gesture pattern of movement.

The eye-tracking profiles (red) represent the distance of eye-fixation from the target key. The low level of calibration in the case of some users, together with the high variability of the number and duration of eye-fixations during the pointing gesture, allow us to consider only the descending phase of the eye-fixation profiles. Nevertheless, the analysis suggests that, as expected, the eye progressively approaches areas close to the target key while the movement occurs. The correspondence between gaze behaviour and arm movement suggests that users have motor involvement in the typing gesture. At this point, the lack of more precise eye-tracking data does not allow us to consider the user's potential linguistic participation. Further commentary on eye-tracking data is provided in the following analyses. The black lines in Figure 3.2 show the distance between the ML classifier-predicted key and the target key. For all users, the maximum prediction distance coincides with the maximum distance of the arm from the key. Then, the distance between the predicted and target key reduces proportionally with the keyboard-finger distance. As expected, the closer the finger gets to the keyboard the better the ML classifier is able to identify the correct key. The level of predictability differs from user to user. Less variable pointing gestures lead to higher prediction scores. As an example, P4's high variability of movements leads to poorer predictability of the finger's final position. On the other hand, users such as P8, P9 and P13, present good predictability scores (distance between predicted and actual key reaching nearly 0 by t = 0).

3.3.1.5 Discussion

If the user is cued by the facilitator to the target key, the pointing gesture should be composed of a rapid ballistic part preceding a longer decelerating tail, where the movement is slowed in order to sense the facilitator's cue and point at the correct key. It can be seen from the users' movement profiles (Figure 3.2), that three users (P8, P9 and partially P7) show a movement profile similar to the one displayed in Figure 3.1b. In fact, they present a rapid decrease of finger distance from the keyboard (at around T = -7, T = -5 and T = -4, respectively) and a longer period with the finger very close to the keyboard before the keystroke. In P8 and P9, this elongated period with the finger closer to the keyboard does not correspond to a reduced distance of the ML-classifier predicted key from the target, nor an adequate reduction of the eye distance from the target key (allowing for lost reliability due to calibration issues). These elongated tails and greater distance between predicted and target keys in P8 and P9 could be indicating a period when the user is sensing and following cues from their facilitator. The other users' profiles (with the exception of P4 who does not have a bell-shaped profile) show a more proportionate, direct, and smooth approach to the keyboard with a higher symmetry between the phases away and towards the keyboard and a shorter period of lingering in the neighbourhood of the target key. Their movements towards the keyboard show a low level of hesitancy, suggesting little influence of sequential cueing. The presence of these two movement profile characteristics suggests, at least, that there is less dependence on cue-sensing in the typing of some users compared to others.

3.3.2 Test 2

If FC users are only involved at the motor, and not the linguistic level, as is hypothesised by the ideomotor perspective, we expect their pointing trajectories to reveal signs of hesitation and uncertainty about the target key. Particularly in the close loop phase of the pointing gesture, their movement trajectory should not be smoothly directed to the target but rather display multiple and rapid changes of direction corresponding to sensing and responding to binary direction cues. Whether movements display rapid and continuous direction change, thus uncertainty with respect to the target key, can be expressed as a function of movements' tortuosity index (TI). In figure 3.1c and 3.1d we represented two different, but not consecutive movements, highlighting in 3.1c a movement with a low level of tortuosity and in 3.1d a movement with a high level of tortuosity. Each figure represents the three-dimensional arm displacement between two consecutive keystrokes. The backward and forward phases of the movement are clear, and the tortuosity index (TI) measure is visualised in the curves and twists of the trajectory. Figure 3.1c shows a trajectory with a low TI value close to 1, which describes a movement with little directional uncertainty. Figure 3.1d shows the lateral changes of direction that could lead to a high TI value.

3.3.2.1 Participants and procedures

These were the same as in Test 1.

3.3.2.2 Methods

To capture differences in trajectory smoothness, we computed a tortuosity index (TI) value. We performed TI analyses separately on the ballistic part of the movement towards the keyboard (from the start to velocity peak), and on the closed loop phase (from the velocity peak to the end of the movement). The velocity peak was computed by drawing the speed profile of each pointing gesture (See appendix II for the calculation of the speed profile). A TI value closer or equal to 1 indicates an almost smooth and straight trajectory. A higher TI value indicates a trajectory with curves and twists.

We derived the TI by calculating the degree of curving of a trajectory. We took the ratio of the actual path length of the trajectory to the Euclidean distance traversed:

$$TI = (L / D)$$

with L referring to the length of the trajectory and D the linear distance between the trajectory endpoints.

Thus, TI values closer or equal to 1 indicate an almost straight-line trajectory. We calculated the tortuosity index on the ballistic and close loop phases each pointing gesture. Then we calculated the average TI for each user. As no control data were collected to test the TI of fully user-controlled pointing, we established a threshold of tortuosity at 1.2 (TI values closer to 1 reflect a linear trajectory towards the endpoint), considering that 7 out of 9 participants showed average TI values under that threshold in the ballistic phase of their movements. We then calculated the percentage of movements below this threshold level of TI for each participant.

3.3.2.3 Results

The results of the tortuosity index analysis are summarised in Table 3.2.

	A Tortuosity index on the antero-lateral dimension						B Tortuosity index by keys probability						
	From movement start to peak velocity			Form peak velocity to end			Keys with low probability to occur (LP)			Keys with high probability to occur (HP)			
	Mean TI (sd)		%<1.2	Mean TI (sd)		%<1.2	Mean TI (sd)		%<1.2	Mean TI (sd)		%<1.2	
P1	1.43	0.74	60.99%	1.77	0.88	19.41%	1.73	0.73	18.88%	1.73	0.86	22.99%	
P4	1.14	0.41	85.56%	1.42	0.70	52.87%	1.48	0.79	50.74%	1.42	0.73	57.06%	
P6	1.15	0.30	83.54%	1.23	0.54	72.22%	1.19	0.51	76.41%	1.15	0.39	79.65%	
P7	1.10	0.32	88.29%	1.94	1.18	22.00%	2.02	1.21	18.04%	1.60	0.80	31.91%	**
P8	1.38	0.73	66.38%	2.16	1.03	7.94%	2.18	1.00	5.08%	2.14	0.97	7.68%	
P9	1.13	0.48	89.82%	1.93	1.23	15.04%	1.87	1.22	15.34%	1.86	1.14	17.01%	
P11	1.15	0.41	82.31%	1.34	0.72	65.17%	1.29	0.53	65.69%	1.26	0.69	73.87%	
P12	1.15	0.36	83.02%	1.25	0.35	56.60%	1.24	0.25	57.63%	1.24	0.24	59.45%	
P13	1.16	0.55	86.52%	1.10	0.21	89.54%	1.09	0.16	89.16%	1.05	0.13	97.36%	**

Table 3.2. Tortuosity index (TI) analysis. The overall TI for each user is presented in (A). The first group of columns shows the TI registered from the start of the movement to the velocity peak. The second group of columns shows the TI registered from the velocity peak to the end of the movement. For each of these groups of columns, the TI mean is reported alongside the standard deviation (sd) and the percentage of movements in which the TI assumes values below the threshold of 1.2 (%<1.2). The TI from the velocity peak to the end of the movement is presented in (B) for low and high probability keys. Results reported indicates a high degree of variability across users. The ballistic phase of the movement shows lower levels of TI as expected. The final part of the pointing gesture shows higher TI values, with some participants (P1, P7, P8, P9) above the threshold on most occasions. In (B), only P7 and P13 show a consistent decrease of TI in the case of high probability keys.

The analysis shows that TI values increase in the latter part of the movement to the target key (Table 3.2A). This may reflect the need for precision in the movement's deceleration phase. It may also reflect an increased degree of uncertainty about the target location The results show wide variability among participants. P4, P6, P11, P12 and P13 have more than 50% of their movement below the threshold of 1.2 and P6, P11, and P13 have at least two thirds. P1, P7, P8 and P9 have on average higher TI values and in most of their pointing gestures they show a TI value higher than 1.2.

3.3.2.4 Discussion

An important feature of these results is the considerable variability across participants. If we consider the final part of the movement (from the velocity peak to the keypress), some participants showed low levels of TI on average and for most of their pointing gesture (P6, P11, and P13). Some other participants showed overall medium levels of TI (P1, P4 and P12). Finally, some participants (P7, P8 and P9) broadly showed greater levels of TI compared with the rest of the group. So, with respect to our initial hypothesis, P7, P8 and P9 and to a medium degree P1, P4 and P12 meet the prediction of hesitancy in the close loop phase. On the other hand, P6, P11 and P13 show a more target-directed pointing gesture that is less consistent with the expected hesitation due to cue-sensing.

3.3.3 Test 3

The ideomotor hypothesis holds that the user is involved at a motor level only, and discovers which key is to be pressed next by sensing a sequence of directional cues from the facilitator. In this perspective, eye-fixations are expected to follow the finger position rather than anticipating and guiding the finger towards the target key. Thus, the eye-movement trajectories should show signs of uncertainty and indecision, while the user adjusts the visual target to the finger position, mirroring the uncertainty and tortuosity of the pointing gesture (Kezuka, 1997; Andersen et al., 2019). In Figure 3.1e and 3.1f, we schematized how the eye-movement trajectory could look if the user is not dependent on the facilitator's cues (3.1e), and if the user is sensing for facilitator's cueing (3.1f). The user who is not cue-dependent should show a direct aiming at the target key with a reduced number of different keys fixated for each pointing gesture (3.1e). A user who is sensing for facilitator's cues would exhibit an increased tortuosity in their aiming at the target key, with an increased number of different keys fixated and higher degree of indecision (3.1f).

3.3.3.1 Participants and procedure

These were as described for Test 1.

3.3.3.2 Methods

We first analysed the average number of keys fixated during each complete pointing and in the close loop phase of movement. We also calculated the percentage of movements in which users fixated on a single key or a maximum of two keys. Next, we calculated the number of key-jumps in eye-fixation during each pointing gesture. This can be a means to detect wandering and uncertainty. For example, given a sequence where the user looks at just two keys (for example "a" and "s"), if the gaze switches several times between "a" and "s", the total number of keys fixated is 2, but the number of key-jumps can be higher. Thus, key-jumps consistently higher than the number of fixated keys could indicate indecision about the target, as we would expect from users sensing and following a sequence of cues. The ratio of the number of key-jumps and the number of different keys fixated was used to derive the directness of eye movements. In direct movements, the number of key jumps should be one less than the number of keys fixated. If the user is sensing multiple directional cues on the way to the target, their eye movements should show less directness.

3.3.3.3 Results

A — Avg number of keys fixated forward pointing

	General mean	General sd	LP mean	LP sd	HP mean	HP sd	
P4	2.00	1.20	2.14	1.199	1.75	1.16	**
P6	1.72	1.01	1.78	1.01	1.53	0.98	
P7	1.68	0.93	1.82	0.99	1.48	0.78	**
P8	3.04	1.35	3.15	1.38	2.80	1.27	*
P9	1.80	1.08	1.86	1.09	1.65	1.04	*
P11	2.08	1.06	2.28	1.07	1.74	0.93	**
P13	1.72	0.87	1.92	0.96	1.46	0.64	**

B — Avg number of keys fixated after the velocity peak

	General mean	General sd	LP mean	LP sd	HP mean	HP sd	
P4	1.19	1.14	1.26	1.16	1.07	1.10	
P6	1.52	0.98	1.59	0.97	1.31	0.99	*
P7	1.58	0.89	1.75	0.94	1.33	0.76	**
P8	2.22	1.50	2.25	1.51	2.15	1.46	
P9	1.61	1.06	1.66	1.07	1.49	1.04	
P11	1.48	0.96	1.64	1.02	1.23	0.78	**
P13	1.48	0.73	1.66	0.83	1.24	0.47	**

*** p-value <0.05 t-test**
**** p-value <0.01 t-test**

	C: movements % user gaze at 1 or less key				D: movements % user gaze at 2 or less key				E: % of movements with linear keyboard eye-exploration			
	General %	LP %	HP %		General %	LP %	HP %		General %	LP %	HP %	
P4	40.3%	31.3%	44.3%	**	73.0%	63.9%	77.8%	**	76.6%	42.6%	80.1%	**
P6	46.3%	41.6%	48.4%		82.6%	78.9%	84.4%		81.4%	86.5%	81.6%	
P7	54.8%	42.6%	57.5%	**	85.9%	78.1%	92.7%	**	83.8%	87.3%	90.6%	
P8	10.0%	9.7%	13.6%		37.6%	35.5%	46.4%	*	67.1%	68.0%	62.0%	
P9	42.9%	39.9%	48.4%		76.1%	75.3%	83.6%	*	86.4%	83.8%	84.1%	
P11	32.6%	22.1%	42.5%	**	73.6%	62.9%	84.4%	**	86.8%	88.4%	86.0%	
P13	48.2%	37.7%	60.9%	**	84.9%	78.6%	93.9%	**	79.2%	74.3%	91.6%	

*** p-value <0.05 Z-proportion test**
**** p-value <0.01 Z-proportion test**

Table 3.3. Eye-tracking analysis. The table A shows the average number of different keys fixated by the participants during their pointing towards the keyboard. Table B reports the average number of different keys fixated in the close loop phase of the pointing towards the keyboard (from the velocity peak to the keystroke). Table C reports the percentage of movements where participants fixated just 1 key. Table D displays the percentage of movements in which participants gaze at 2 different keys. Table E represents the percentage of movements where participants show a linear exploration of the keyboard, signalling no back-and-forth fixations over the same key. For all the analysis, we reported the general values (General) deriving from the analysis of all the pointing gestures, and the values deriving from the movement analysis according to keys probability, (keys with low and high probability to occur, LP and HP respectively).
The results reported in this table refer to the hypothesis presented in Study test 3 and Study 2 test 2.

Table 3.3A shows the average number of different keys fixated over the whole pointing gesture. In the execution phase of the movement (from the start of movement to the keystroke), all users gaze on average 2 or less keys, with the sole exception of P8, who looks at 3.04 keys on average. When just the close loop phase is considered (velocity peak to keystroke, Table 3.3B), the average number of different keys fixated drops for each user to values closer to 1.5. Again, P8 is an exception with 2.22 keys fixated on average. All participants but P8 fixate on just one key in at least 30% of their pointing movements (Table 3.3C). Overall, all participants except P8 fixate two different keys or less at around 70% of their pointing gesture (Table 3.3D). The only exception again is P8. This participant looks on average at more than 3 keys during their whole movement looks. Only 37% of their movements involved fixating of two or less keys and 10% involved fixation on one key or less. The key-jumps analysis (Table 3.3E) shows the percentage of pointing gestures with a linear exploration of the keyboard. The results shows that all the users' eye movements are linear on most occasions, with some variability.

3.3.3.4 Discussion

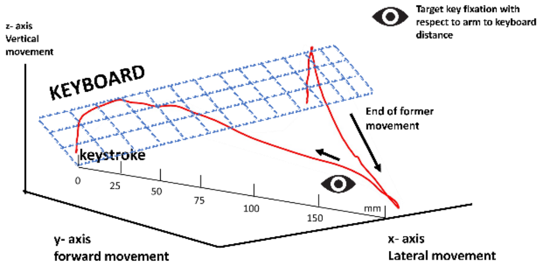
Only P8 shows an eye-fixation pattern that is consistent with the wandering that is expected when the user depends on a sequence of cues from the facilitator. All other users display eye-fixation behaviour with no clear signs of directional hesitancy or wandering. This could be in part due to the poor calibration quality of eye-tracking data (see Appendix I – Data acquisition). However, the number of different keys fixated correlates well with TI values, suggesting that our use of eye-tracking data was able to address users' visual indecision.

3.4 Study 2

3.4.1 Test 1

If the user's pointing finger approaches the target key by following a sequence of directional cues and not a user-driven linguistic choice, their eye-fixations should travel to the next key that appears to be cued (until the next cue changes the likeliest target key, etc.). The distance between the eye-fixation location and the target key should progressively reduce alongside the finger-to-key distance, as the finger (influenced by the facilitator's cueing) should guide the visual fixation and not vice versa. If, on the other hand, the user is linguistically involved and knows the next key to be pressed, their eyes should lead their finger to the key location, arriving earlier with a less variable trajectory (Land and Furneaux, 1997; Zong et al., 2023). This would indicate that the user knows early on which key is next, indicating that they are linguistically involved and not totally dependent on progressive directional cueing.

In figure, 3.3 (a, b) we show schematic representations of these two possibilities. In Figure 3.3a, the target key is fixated when the finger is at the beginning of its forwards phase. In Figure 3.3b, however, the user is gazing at the target key only when the arm is very close to the keyboard. Similarly red lines in figure 3.3a and 3.3b display these two possibilities. In 3.3a, the distance between the target key and the fixated key reaches values close to 0 in the early phase of the forward movement. This is taken as an indicator that the user chooses or knows the next to be typed key. In 3.3b, the distance reduces at a slower rate than the distance between the finger and the keyboard. This does not point to a linguistic choice by the user.



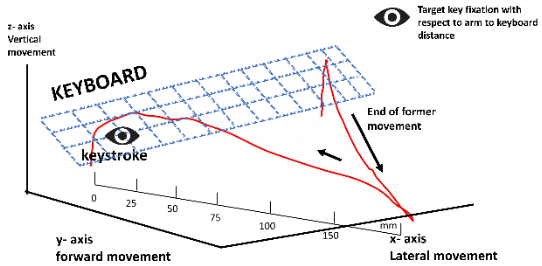


Fig. 3.3. Relation between target key's visual hit and finger to keyboard distance. In this figure we displayed the trajectory described by two pointing gesture and we computed when along the pointing trajectory the user visually hit the target key. In 3.3a the user is fixating the target key when the movement is at the beginning of the forwards phase. This behaviour is compatible with users that are linguistically engaged and therefore predict the following key. In 3.3b the user is gazing at the correct key in the final phase of the movement. This behaviour is compatible with users that are not linguistically involved from a linguistic standpoint. The figures also report a simplified representation of the finger to keyboard distance ranges used for the analysis.

3.4.1.1 Participants and procedure

These were as described for Study 1, Test 1.

3.4.1.2 Methods

We investigated the relationship between the distance of eye-fixations from the target key and the distance of the pointing-finger from the keyboard. For each user and each pointing gesture, we calculated the time of their final fixation on the target key (or the last fixated key for users whose eye-tracking calibration was of low quality) during the pointing movement and then calculated the pointing arm's position at that time.

As in the TI analysis, we computed the arm position by determining the planar distance along the keyboard, excluding the vertical component (movement away and towards the plane of the keyboard. The inclusion of information from the vertical dimension had the potential to introduce ambiguity into the analysis results. For instance, a user's finger might hypothetically be precisely positioned directly above the designated key but still higher above the keyboard. In such a scenario, the finger may not be vertically close to the target key but the decision about the target would be over. Consequently, omitting the vertical component ensured a more focused and reliable assessment of the arm's proximity to the target key.

Only P8 and P13 had a precise eye-tracking calibration, with the eye-position registered matching the actual eye-position perfectly. For these users, we referred to the frequency with which the users gazed at the target key in relation to the finger's planar distance along the keyboard. For all other users, their target key was derived from the last eye-gaze position. In the analysis, we considered the last key-fixated for each pointing gesture as the target position of the pointing. Then we calculated the distance of the finger when the target key was fixated.

We derived 6 ranges of arm to keyboard distance (<25mm, 25-50 mm, 50-75 mm, 75-100, 100-150 mm and >150 mm) and calculated the proportion of pointing gestures in which the eye fixated the target or final key with the arm being in that range of distance.

The relationship between target fixation and the finger's distance from the target was then examined in the context of eye-movement variability and the percentage of screen-looking. Eye-movement variability analysis is reported in Study 1 – Test 3. The percentage of screen looking reports how often users directed their gaze towards the text editor, the word document that registered their typing. It was calculated as the ratio between the number of pointing movements in which the users looked at least once at the text editor divided by the total number of pointing gestures.

3.4.1.3 Results

Table 3.4A reports the average finger-to-target distance when users fixate the target key and the proportion of the movement (within the ranges <25mm, 25-50 mm, 50-75 mm, 75-100, 100-150 mm and >150 mm) during which the target key is fixated. It is evident that, for the majority of users, eye-fixation on the target occurs when the finger is about 30-40 mm from the keyboard, indicating a proximity to the target. However, exceptions are observed in the cases of P6, P7, and notably, P13. For these individuals, the target is fixated earlier, at average distances of 69 mm, 74 mm, and 187 mm from the keyboard, respectively. In the case of P4, P7, P8, and P9, the target key is fixated when the finger is less than 25 mm from the keyboard in approximately 50% of pointing gestures. In contrast, P13 directs their gaze towards the target key when their arm is more than 150 mm from the keyboard in 62% of their pointing gestures.

A

Finger-keyboard distance when the target is visually hit

	Average distance (mm)		**% movements the eye hits the target when the finger is n far from the keyboard (mm)**					
	mean	*sd*	*n <25*	*25<n<50*	*50<n<75*	*75n<100*	*100<n<150*	*n>150*
P4	29.6	28.9	47%	20%	8%	6%	2%	0%
P6	74.2	75.9	26%	23%	8%	6%	7%	15%
P7	23.9	27.0	62%	16%	5%	3%	2%	1%
P8	39.9	32.2	44%	24%	20%	7%	4%	1%
P9	38.2	76.3	70%	9%	1%	0%	1%	9%
P11	69.3	60.4	26%	22%	12%	10%	15%	10%
P13	187.7	107.1	11%	5%	6%	4%	9%	62%

B

% of movements the user looks at the screen after the previous keystroke	
P4	67.12%
P6	58.54%
P7	88.68%
P8	4.32%
P9	48.20%
P11	56.06%
P13	25.70%

Table 3.4: Analysis of the relationship between arm position and the visual hit of the target key (A). Analysis of the percentage of screen looking (B). In table A, for each user we report the average distance (mm) of the finger from the keyboard when the user hit for the first time the target key and does not change the visual fixation before the keystroke. Then table A report for each user the percentage of movements the visual hit happens when the finger is at 6 different distance ranges. In general, most participants look at the target key when the finger is very close to the keyboard (between 30 to 40 mm). The exception is represented by P6, P7 and P13 in particular, with the target hit on average when the finger is respectively 69, 74 and 187 mm away from the keyboard. Considering the percentage of movements, P4, P7, P8 and P9, in around 50% of their pointing gestures visually hit the target key with the finger being less than 25mm far from the keyboard. Noteworthy, P13 looks at the target key when their finger is quite far from the keyboard (>150mm) in 62% of the pointing gestures. Table B reports the percentage of time users gaze at the screen after their previous keystroke. It clearly emerges a clear pattern where the users, with the only exception of P8, constantly refers to the computer screen during their pointing phase. The constant reference to the screen during the accomplishment of the forward movement, may be responsible for the lack of visual anticipation of the target key from the user, as the eye may return back to the keyboard when the arm is already pointing at it.

3.4.1.4 Discussion

The interpretation of these results should be integrated with the analysis described in Study 1, Test 3. In particular, the acknowledgment of a late visual hit of the target key, described in most users, should be integrated with the analysis of the number of different keys fixated and with the percentage of time users visually refer to the screen (both reported in table 3.4B).

The results show that many users gaze at a small number of different keys during the pointing gesture (shown by some users in Study 1 – Test 3) and fixate the keyboard and the target just on the final phase of the movement. In the preceding, ballistic phase, most of the users look consistently at the PC screen, where the text editor is displayed. Again, the only exception is represented by P8 who looks at the screen for a small percentage of pointing gestures (<5%).

The association between a reduced number of different keys fixated together with a high percentage of screen-looking describe a complex pattern of arm-visual behaviour in which after the stroke of the former key and in the early phase of the movement execution, the participant is looking at the screen. Then users direct their gaze at the keyboard with little signs of visual indecision but with their finger being very close to the keyboard. This behaviour makes it difficult to ascertain visual anticipation of the target key. The evidence that users are looking at the screen after the keystroke can be interpreted both as a motor need or a linguistic one. In the former case, the user would look at the screen to check whether the key was pressed correctly. In the latter case, users would refer to the screen to check the linguistic string to program the following pointing gesture. These data could not distinguish these.

3.4.2 Test 2

The ideomotor perspective suggests that FC users are involved at the motor level, but not at the linguistic or communicative levels. If so, the letter to be typed must be cued by the facilitator, and whether the next letter is a low or high probability letter, given the linguistic context, should not make a difference to the paths taken by the pointing finger or the eye. Conversely, if the user is active from a linguistic standpoint, movement behaviour should reflect effects of context-driven linguistic facilitation (Grudin, 1983; Pinet et al., 2016; Andersen et al., 2019).

3.4.2.1 Participants and procedure

These were as described for Study 1, Test 1.

3.4.2.2 Methods

We evaluated differences in inter-keystroke interval (IKI), path length, TI and eye-tracking behaviour as these relate to the probability of the next key to be typed. We developed a tool to calculate the linguistic probability for each key to be selected given the sequence of letters that preceded it. For example, given the Italian word /acqua/ it was possible to calculate the probability that after the string of characters /acqu-/ the character /a/ could follow. This calculation considered not only the probability of occurrence given the contextual character string but also the frequency of occurrence in the Italian written language. For example, in Italian there are only three combinations possible given the string /ca/. Be this combination /t/, /f/ and /l/, to create the full words /cat/, /caf/ and /cal/. The probability therefore for each key to be selected would be .33 each. However, if the word /cat/ has a greater occurrence in the Italian written language, the probability of /t/ to be selected should be higher than the one of /f/ and /l/. For this purpose, we used the CoLFIS (Corpus e Lessico di Frequenza dell'Italiano Scritto), which consists of more than 118,000 words forms. To each word form a frequency score is assigned (the higher the score the more probable the word is used). The probability of a given letter was therefore calculated as follows:

Given x is the sum of the frequency score of the previous string /acqu-/ and y is the sum of the frequency score of the previous string plus the target key /acqu-a/, the probability of the key is

$$(y/x) * 100 \quad (1)$$

The IKI analysis compared the average interval of movement directed at keys of low (LP, <50%) and high (HP, >50%) probability. To minimize outlier variability, only movements that lasted at least 0.5 s and less than 2 s were considered. Strokes of the spacebar (high probability) and first character of each word (low probability) were excluded. The space bar (that usually has probability score higher than 60%) was not considered as it is wider, and any speed advantage could be due to the increased target area. The first letter (that all has probability score lower than 15%) was removed as the inter-word latency might be influenced by factors not typing-speed dependent (as lexical latency, for example).

Statistical analysis of the IKI difference was conducted using a t-test iterated 10 times on randomized samples of IKI intervals (300 observations per probability condition). In each iteration, a sample of 300 IKI intervals was collected for both the high probability (HP) and low probability (LP) conditions. The t-test results from each iteration were then averaged.

To supplement the IKI analysis, we computed the average distance travelled by the users' arm for each probability condition (High and Low) in both the forward and backward phases of the movement, and the average speed (distance/time) of the pointing gestures for each condition, in both the backward and forward phases of the pointing gesture. A Welch's t-test was performed to evaluate average differences between path lengths and typing speed (p-value <0.01). According to the ideomotor hypothesis no significant difference in terms of IKI should be expected.

Similarly, TI values and eye-behaviour data were addressed to verify differences according to the linguistic context. With regard to TI variation in relation to key probability, we categorized TI values into two groups: the HP group contained the TI of movement aiming at high probability keys (>50%), and the LP group of the TI values of movement pointing at low probability keys (<50%). Then we performed a Welch's t-test (p-value <0.01) to evaluate any statistical differences between the two groups.

The average number of keys fixated, and the linearity of keyboard exploration was also addressed according to key probability. Again, we categorized the eye-behaviour data into two groups: the HP group where we collected the number of keys fixated and the number of key jumps when the pointing gesture was aimed at high (>.5) and low (<.5) probability keys. A Welch's t-test (p-value <0.01) was set to evaluate statistical differences in the number of keys fixated between the two groups. A two Proportion Z test (p-value <0.01) was set to evaluate differences in the percentage of linear movements between the two groups. According to the ideomotor hypothesis no significant difference in terms of IKI should be expected.

3.4.2.3 Results

	A					B					C					D				
	Inter keystroke interval					Path travelled backwards (mm)					Path travelled forward (mm)					Pointing speed forward (mm/ms)				
	LP		HP			LP		HP			LP		HP			LP		HP		
	mean	*sd*	*mean*	*sd*		*mean*	*sd*	*mean*	*sd*		*mean*	*sd*	*mean*	*sd*		*mean*	*sd*	*mean*	*sd*	
P1	1.20	0.25	1.11	0.28	**	57.6	49.1	64.9	48.9	*	152.0	44.1	148.2	44.1		1.7	0.6	1.9	0.6	**
P4	1.15	0.30	1.04	0.30	**	2.8	10.1	2.9	8.0		81.2	47.6	66.3	46.9	**	0.8	0.4	0.7	0.4	
P6	1.11	0.25	1.01	0.24	**	106.6	70.9	117.8	67.0	**	197.6	53.8	195.2	52.2		2.6	0.9	2.9	1.0	**
P7	1.12	0.32	0.89	0.27	**	71.1	58.1	61.8	60.4	**	158.4	48.5	134.5	60.7	**	2.0	0.7	2.1	0.8	**
P8	1.55	0.23	1.54	0.24		64.6	49.5	67.5	49.4		153.6	44.8	147.9	42.7	*	1.3	0.5	1.2	0.5	
P9	1.46	0.26	1.47	0.27		175.5	85.5	187.3	84.3	**	258.8	75.6	259.4	75.8		2.5	0.8	2.5	0.8	
P11	1.42	0.28	1.35	0.26	*	96.2	70.9	98.1	72.3		182.0	63.7	171.4	67.9	**	2.0	0.8	2.0	0.9	
P12	2.68	0.52	2.59	0.48		115.8	58.1	132.0	55.7		204.4	35.9	209.3	23.6		1.5	0.3	1.5	0.2	
P13	1.60	0.21	1.51	0.22	**	192.6	54.2	200.0	52.3	**	278.2	28.1	276.5	28.7		2.8	0.5	3.0	0.5	**

*** p-value <0.05 t-test**

**** p-value <0.01 t-test**

Table 3.5. Inter-key stroke analysis and Path length analysis and speed analysis. The table A report the analysis of the Inter-key stroke (IKI), the analysis of the distance accomplished by participants in their return (away from the keyboard, table B) and pointing gesture (to the keyboard, table C), and finally the analysis of participants pointing speed in the forward phase of the pointing movement (table D). In all cases, the table report a comparison between movements directed to keys with a low probability to occur (LP) with keys with a high probability to occur (HP). Statistical significances result from Student's t-test.

6 participants (P1, P4, P6, P7, P11, P13) show a decreased IKI when they have to press keys that have a higher probability to occur after a given string of characters. In 4 cases (P1, P6, P7, P13) the

IKI differences are associated with, and therefore can be explained by, speed differences in the forward phase of the movement (pointing at the keyboard). In the case of P4 and P11, IKI differences can only be explained by a reduced distance travelled in the forward phase of the movement. Given the P4 does not have a proper return gesture, IKI differences may just reflect the facilitation provoked by keys displacement that favour keys that are more likely to occur close in a string. In the case of P11, considered the consistent length of the return gesture (around 96 mm), it is probable that IKI differences reflect participants arm's relocation in the return phase of the movement. No significant differences are detected for P8, P9 and P12.

The IKI analysis is displayed in Table 3.5A. The results show that 6 participants (P1, P4, P6, P7, P11 and P13) have significantly shorter inter-keystroke intervals when they press high probability keys. On the other hand, P8, P9 and P12 do not show IKI difference linked to key probability. For some participants (P1, P6, P7, P13) these IKIs differences can be explained by variations in the pointing speed (Table 3.5D), with high probability keys being pressed significantly faster than low probability keys. For P4 and P11, the IKIs difference is associated with a significantly shorter trajectory to high probability keys (Table 3.4C). These trajectory differences according to the key's probability are common across all participants, with significant differences measured for P7 and P8 along with P4 and P11.

The differences measured in the trajectories' lengths may reflect the distances between keys. The qwerty interface is designed to favour the proximity of keys that are likely to occur in bigrams or trigrams, therefore it is plausible that the next high probability letter in a sequence tends to be closer on the keyboard. This explanation seems to only fit the case of P4. This participant does not show a clear return gesture but rather going directly from key to key.

In the case of P11, the decreased trajectory length of the forward movement for high probability keys comes with little difference in the amplitude of the return gesture (Table 3.4C, around 100 mm for P11 in both probability conditions). This uniform return gesture, shown by P11 should remove any spatial facilitation provided by key positioning.

In general, the users who show significant path variability according to key probability also show a more variable movement profile (see P7 and P11 movement profile in figure 3.2, Study 1 - Test 1). In the case of P7, a higher pointing speed is associated a decreased return gesture length and consequently a reduced forward path trajectory. For P7, it seems that when it comes to typing keys that are almost certain to occur in the contextual string, the movement pattern is altered to promptly reach the target key. In P6, P8, P9, P12 and P13, no significant differences are observed in the lengths of trajectories. However, the typing speed of P6 and P13 significantly change, with increased speed associated to higher probability keys.

Overall, of the six participants that show IKIs differences, five (P1, P6, P7, P11, P13) show a significant modification of motor behaviour that is consistent with the linguistic context. Only P8, P9 and P12 show no sensitivity to key probability.

TI results according to key probability are displayed in Table 3.2B. No significant differences were detected in TI according to key probability, with the only exception of P7 who strongly reduces by 0.40 the tortuosity of his movement when keys with higher probability are selected. Also, P13 shows some significant differences in terms of TI values a front of a TI decrease of 0.04.

Regarding the eye-tracking behaviour (Table 3.3), certain users (P4, P7, P11, and P13) consistently exhibit substantial performance enhancements when pointing at keys with a higher likelihood of occurrence. This improvement is indicated by a broad and statistically significant reduction in the average number of keys fixated per pointing gesture, coupled with a statistically significant increase in the percentage of pointing gestures involving a linear exploration of the keyboard (verified through two Proportion Z tests with p-value < 0.01). Consequently, it appears that the eye behaviour of these users is influenced by the probability of the key to be pressed.

The remaining users also display some indications of linguistic facilitation, as they demonstrate a general decrease in the average number of keys fixated throughout the entire pointing movement and in the percentage of movement with fewer than 2 keys fixated when keys with higher probability occurred. However, this difference is not consistently maintained when analysing only the closed-loop phase of the movement or the percentage of movements with only 1 key fixated.

3.4.2.4 Discussion

The results of this test show clear evidence, in some but not all participants, that their movement characteristics change according to the probability of occurrence of the next letter to be typed. Thus, at least some FC users' behaviour suggests that they are aware of the linguistic context in which they are typing. This linguistic contribution, even if it is partial, might be expressing a developmental process whereby literacy is being acquired. We return to this point in the general discussion.

3.5 Overall consideration

Our overall goal in this chapter was to investigate whether FC users were involved in the typing task at a higher level than just the motor component. The literature agrees that FC users participate in the motor control component of the pointing gesture. This level of involvement would be expected given that there are instances of FC where the facilitator provides touch only to the shoulder or back. The key question in the present chapter was whether users' involvement extended beyond the motor level to the linguistic one. We analysed users' effector and eye movements for signs of dependence on their facilitator's cuing, and we also investigated whether the user's movements varied according to the linguistic context of the typing. As a general trend, these two approaches produced convergent patterns – users who showed less indication of cue-dependence also showed more consistent signs of linguistic context-awareness. The implication is that an explanation of FC typing that is based entirely on facilitators' cuing is unlikely to be complete. There are signs both of linguistic participation and individual differences. In this discussion, we first consider the participating FC users' data patterns before commenting on the general implications and study limitations.

Based on similarities in behaviour across the range of measures, the participants may be placed in three groups. Group I (P6, P11, P13) showed fewer signs of cue-dependence and clear indications of linguistic contribution. Group II (P8, P9) showed little suggestion of linguistic contribution. Group III (P1, P4, P7, P12) presented a mixed profile.

3.5.1 Group I (P6, P11, P13)

These users' movement profiles showed a symmetrical ratio between the return gesture (withdrawing the arm towards the body following a keystroke) and the forward component (moving towards the next key to be pressed) of the movement. The arm-keyboard distance decreased quite linearly and no period of finger lingering in the neighbourhood of the keyboard was detected. The distance between the predicted and target key decreased proportionally with the arm-keyboard distance. In addition, these users showed lower TI values, lower number of different keys explored, and more linear exploration of the keyboard than the other groups. Alongside these results, these three participants exhibited consistent signs of contextual linguistic facilitation, as shown by reduced inter key-stroke interval for more probable keys, increased speed (P6 and P13) or arm relocation (P11), and eye-fixation efficiency (P11 and P13) for high probability letters. P6, P7 and particularly P13 also often visually fixated the target key when their finger was still quite far from the keyboard. Notably for P13, the target key was fixated while the finger was about 15 cm from the keyboard.

3.5.2 Group II (P8 and P9)

P8's behavioural patterns did not show much indication of linguistic contribution. During the approach towards the keyboard, P8 exhibited an extended period with the finger lingering in close proximity to the keyboard rather than a direct and steady approach to the key. Examination of the distance between the predicted key and the target key revealed a delayed predictability of the final target in relation to the arm-keyboard distance. Additionally, P8 demonstrated elevated levels of TI and a meandering visual exploration of the keyboard. The pointing gesture involved eye-fixations of an average of three different keys, and during the close loop phase, an average of two different keys. Among all participants, P8 exhibited the highest values for TI and the number of keys fixated, along with the lowest occurrence of pointing with a linear visual exploration of the keyboard. These metrics, assessing uncertainty and indecision in movement, suggest a dependence on cues from the facilitator. It is noteworthy that P8 also did not display significant behavioural changes in response to contextual linguistic features. There was no discernible improvement in speed or consistent eye-behaviour when the context called for a highly probable key. Moreover, there were no clear signs of visual anticipation of the target, as the finger was registered, on average, in close proximity to the keyboard when the gaze reached the target key. Additionally, P8 infrequently engaged with the screen displaying the typed keys. Thus, in P8, there is a lack of clear indication of linguistic participation, and many signs of dependence on the facilitator's cues.

The findings for P9 echo a similar pattern. The movement profile is marked by a prolonged period with the finger lingering in close proximity to the keyboard. P9 also exhibited elevated levels of TI compared to the rest of the group. In contrast to P8, the analysis of eye behaviour did not reveal a meandering or erroneous visual exploration. P9 consistently directed attention to a limited number of different keys during each pointing gesture, maintaining constant engagement with the editor screen. This continual reference to the screen may explain why P9 looked at a reduced number of different keys during a pointing movement and the delayed visual fixation on the target key with respect to the arm-keyboard distance. P9 also did not display consistent behavioural changes associated with the linguistic context. Visual fixation on the key target occurred when the finger was, on average, in close proximity to the keyboard. With the exception of eye-gaze (Study 1, Test 3), P9's behaviour consistently suggests participation largely at the motor level only.

In this group, users exhibited limited evidence of contributing beyond the motor level within the theoretical and hypothesis framework we established for this study. Consequently, the parameters we investigated might not have been sufficiently tuned to detect contributions beyond behavioural idiosyncrasies potentially arising from dyspraxia, visual processing issues, or motor planning/execution difficulties.

3.5.3 Group III (P1, P12, P4 and P7)

For P1 and P12, the analysis is unfortunately partial due to the absence of eye-tracking data due to file corruption. In the case of P1, the movement profile exhibited considerable variability in the pointing gesture. However, on average, an elongated tail in the close loop phase was not observed. The distance between the predicted and actual target key consistently decreased with the arm-keyboard distance. P1 displayed high absolute levels of TI, extending even into the ballistic phase of the return gesture. However, P1 showed some signs of linguistic participation, as evidenced by increased pointing speed, and reduced inter-key-stroke interval for keys with a higher probability.

P12's movement profile had an elongated tail, indicating a prolonged period with the finger in close proximity to the keyboard. Additionally, the decrease in distance between the predicted and target key was less rapid than the finger-keyboard distance. Whereas, P12 showed low levels of TI, there were no significant differences in pointing speed as a function of key probability.

Among all participants, P4's pattern was the least readable. P4's movement profiles lacked a clear return gesture. P4 went directly from key to key instead. As the movements were mainly lateral and lacked the forward component, the plotting of the pointing gesture did not return a clear movement profile. Also, the TI of P4's pointing gesture came in at a medium level as the forward component was absent. IKI differences in P4's case were solely determined by inter-key distance rather than by increased pointing speed or arm relocation. P4 did not show visual exploration of the wandering type on most occasions. As in the case of P9, the smaller number of different keys visually explored may have been due to looking frequently at the screen. This may also explain why the visual anticipation of target keys occurred with the finger very close to the keyboard. Differently from P9, however, P4 showed consistent eye-behaviour changes consistent with key probability, with better eye-fixation performance for higher probability keys.

Referring to our hypothesis, Study 1 Test 1 and Study 1 Test 2 could not be directly evaluated. In Study 2, Test 1, P4 met our hypothesis, as the eye hit the target key with the finger being very close to the keyboard. In Study 1, Test 3 and Study 2 Test 2 P4 did not meet our expectations.

In the case of P7, the movement profiles were similar to P8, P9 and P12, with an elongated period with the finger close to the keyboard and the distance between the predicted and target key decreasing slower than the finger-keyboard distance. The TI of P7's movements was at medium to high levels, signalling a quite wandering and tortuous movement toward the keyboard although not matched by a wandering-like eye behaviour. The constant screen-looking may have influenced this data, together with the late visual-fixation of the target key. What should be noted about P7 is the significant behavioural differences measured according to key probability. This difference occurred at all levels: inter-keystroke interval, pointing speed, visual exploration and, only in P7, also in movement tortuosity. What emerged clearly from the data was a complete change in the pointing and looking behaviour when the linguistic context called for a very probable key.
With a reference to our hypothesis, P7 met our expectations in Study 1-Test1, Study 1- Test2 and Study 2 – Test1, but not in Study1 Test 3 and Study 2 Test 2. Little can add to this framework. On

some occasions during the data collection P7 manifested some decoding skills by spontaneously reading out loud something he typed.

3.6 General discussion

As is clear from the preceding section, the most salient feature of the whole dataset is the extensive variability among the users in their pointing gestures as well implied linguistic engagement. As the diversity in FC methods extends also to the level of support provided by the facilitator and their linguistic or communicative involvement, any uniform conclusions about the process are best avoided. Instead, the observed variability should encourage a shift towards fostering the application and evaluation of FC on an individualized, case-by-case basis, rather than treating the technique as a uniform and monolithic approach applicable (or not) universally to all users. The objectives of FC interventions should be custom-designed to align with the unique competencies, needs, and possibilities of each user and of the user-facilitator duo, with continual assessment of indicators of development. The value of using the technique should be judged within the context of the individually tailored goals.

The goal of the reported work was to ascertain whether FC users, beyond controlling their movements, also contribute at the linguistic level. Some of the tested users showed signs of linguistic engagement, as indicated by lower levels of arm and eye movement uncertainty and by changes in behaviour correlated with linguistic context. These features were not recorded in the behaviour of some other users, for whom only motor involvement appeared certain. For such cases, future work could seek to better understand how they might read facilitators' cues as well as they do.

Existing studies on typing dynamics suggest that features related to key position and key frequency affect typers' inter-keystroke interval (Gentner et al., 1988; Scaltritti et al., 2016), while keys that are more predictable, thus more probable to occur in a given strings, entail a more direct visual exploration of the keyboard (Andersen et al., 2019). Interestingly, Andersen's study was based on the analysis of Ouija board sessions, a typing dynamic that has often been compared to FC. The study showed participants could predict the next letter on a Ouija board when instructed to spell a specific message. Their eye movements fixated on the intended character. In contrast, during genuine Ouija sessions (where the message is unknown), eye movements initially wandered across the board. However, as the message unfolded, participants' visual exploration became more focused. The study confirms our hypothesis that people anticipate the next letter during typing as a result of their knowledge of the message to be typed. This awareness leads to more precise eye movements, when focusing on the expected character. These results suggest a connection between improved eye focus and a user's involvement in the task, supporting our interpretation of the results produced in this study.

It should be noted that FC represents a strictly sequential typing pattern. Not only are the keys pressed one at a time, in most cases the planning of each typing gesture is independent from the other. Thus, the time required to type a simple word is stretched. Such stretched typing times lead to two ways of interpreting the nature of the behavioural changes observed according to key probability. This depends on whether the complete word form is accessible to the FC users at the beginning or becomes so later on, when a part of the word has already been typed. According to Scaltritti (2016), the activation of linguistic processes cascades into linguistic output generation. Thus, while the word form is retrieved at the beginning of the movement, the activation of orthographic processes happens during the movement execution. This leads to an improved typing performance (decreased IKI) while the orthographical form is unveiled, and the orthographical buffer is highly activated. The delayed typing mechanics experienced by FC users can be consistent with such description. The more the orthographic trace is activated the easier is the movement planning. At the same time, it is possible that these behavioural changes are due to a late unveiling of the word form, with the user being faster in typing only once they recognise the word that needs to be typed. This latter option calls for a user-facilitator co-creative process at word-level, while the former entails a co-creative process at the sentence level. Both interpretations are possible in light of our data but could not be tested further. It could be argued that changes in motor behaviour associated with linguistic context features actually mirror linguistic effects on the facilitator and their way of cueing, rather than signs of users' linguistic involvement. While the analyses provided in this chapter cannot, by themselves completely eliminate this possibility, given the complex, continuously evolving and intertwined dynamic of FC, some considerations can be presented.

If increased typing speed and more precise visual exploration of the keyboard were the result of better cueing by the facilitator, this could only be the result of a less hesitant facilitator during the completion of the pointing gesture. Assuming that the users were completely unable to assign linguistic value to what they were cued to type, the facilitator would still need to provide a progressive and binary cueing of users' pointing gesture. This phase cannot be skipped: more probable keys are not easier to cue. Nevertheless, it could be assumed that facilitators could show less hesitancy when unconsciously cueing keys that are more likely to occur. Therefore, linguistic contextualization would work not on the physical act of cueing but rather on the facilitator's knowledge that unconsciously drives the cueing. According to this view, differences in facilitators' ways of cueing according to key probability could directly impact users' tortuosity index. Among the participants described in this work, only P7 showed a significant change in tortuosity according to contextual linguistic probabilities. Only for P7, changes in the tortuosity index were associated to linguistic probabilities. This result may leave open the possibility that the behavioural changes observed are driven by a linguistic facilitation operating on the facilitator (therefore on their cueing) rather than on the participant's improved knowledge of the word to type.

All the other participants showed no change in tortuosity therefore in the hesitancy of their movement in relation to key probabilities.

Moreover, if behavioural changes were the result of linguistic facilitation of the facilitators, all users should benefit from this. In particular, users who are assisted by facilitators that show linguistic contextualization should demonstrate contextual facilitation (increased speed and improved visual exploration). The data presented in this chapter, however, show that users differ in terms of linguistic facilitation even when they shared the same facilitator: P7 and P13 who showed increased typing speed and more efficient visual exploration of the keyboard when they typed more probable keys differ respectively from P8 and P9 with whom they share the facilitator but who did not show increased speed (P8 and P9) or improved visual exploration (P9). Since linguistic facilitation would work on facilitators' knowledge that drives the cueing rather than in the cueing itself, these differences are hardly explicable if we do not allow users' active linguistic engagement.
In a recent paper, Beals (2022) suggests that, in FC or FC-like method, users can predict or orientate their gaze towards the to-be-typed key without being aware of what they are typing or what they are conveying through their typing, just on the basis of their practice with the facilitator or statistical knowledge of how words are formed. In this perspective, participants would be able to type the character "g" given the string "do", to form the word "dog" without knowing what /dog/ actually means. This proposal merits exploration and commentary. Let us assume that participants are just following a statistical computational pattern that allows them to auto-complete strings of characters generating existent words. In this scenario, the participants would have the ability to decode a half-generated character string and complete it on the basis of a word form stored somewhere in the mnemonic system. Here, however, we show how behavioural changes are not determined by frequencies at character level, but rather at word level. As such, the string had to be decoded, compared with an existent one, and then completed. In doing so, all components of the dual cascade model (Coltheart et al., 2001) were adhered to, except for accessing the semantic system. Debating whether being able to accomplish such a task would or would not prove someone's literacy skills should not overshadow the learning process the participants have been through. Instead, it should foster further investigation of whether FC-like systems can be re-adapted and exploited in a learning and developmental perspective. This latter perspective is the one we hold here and in Chapter 2.

Any acknowledgement of users' linguistic participation does not allow us to further interpret and evaluate users' communicative participation, which is their internal intention to express the contents that are typed. However, the results are compatible with what we have described **in Chapter 2**. There we hypothesized that texts produced with FC are the result of a co-creative process that engages both the users and their facilitators. We submit again that the utility of a technique that may enhance users' linguistic competencies by utilizing touch-based assistance in regular practice and collaborative creation of linguistic output merits further consideration and investigation.

3.7 Limitations of the present study

Salient among the limitations of this work are some of the technological difficulties inherent in gathering limb and eye-movement data from participants while they behave freely. The calibration of the eye-tracking glasses was challenging, in some participants due to their visual deficits (e.g., strabismus). We also lost some eye-movement data files due to corruption problems. In particular, it would have been interesting to study the facilitators' eye-movement data. This was not possible as no overlapping eye-tracking session was accessible. It would have allowed us to investigate whether facilitators anticipated or followed the user in visually fixating target keys. Whether the facilitator looks at the keyboard has always been a matter of debate since a facilitator not looking at all at the keyboard would be an indirect but clear and nearly decisive clue of users' linguistic contribution. From a qualitative analysis of the sessions' video recordings this is not the case of the participants we analysed. Even without accessing facilitators' eye-tracking performance it was clear from the video recording that the facilitator looked either at the screen or at keyboard during the typing task.

However, these observations and the absence of the facilitators' eye-tracking performance do not particularly affect our analysis and its discussion. The involvement and active participation of the facilitator does not preclude the user's active involvement. In the co-creative process perspective we adopt, there is room for both the user and the facilitator to contributed to the task. As such, the acknowledgment of users' participation would not be affected by eventual indicators of facilitators' engagement with the task. From co-creative process perspective, it would not be surprising if the facilitator anticipated or predicted the keys pressed by the user.

Another limitation of this study was the absence of a control group. On several occasions in our analyses, we had to derive our interpretations based on inter-participant differences or differences based on probability features of the linguistic context. Our data analysis would have been helped by having motor and eye-tracking data from users we actually knew were controlling the typing tasks or who were voluntarily and consciously cued by their facilitator.

3.8 Conclusion

The present studies illustrated significant behavioural variations across FC users, suggesting different levels of linguistic engagement spanning little to no linguistic engagement to consistent indications of linguistic participation. The indications of linguistic engagement suggest that touch-based assistance may be able to contribute to the development of literacy skills in the case of some users. The level of variability across users also prompts a call for user-centric evaluations of the efficacy, outcomes, and objectives of FC. As previously introduced in chapter 2, the application of touch-based assistive techniques would greatly benefit from adopting a developmental framework that incorporates intermediate and measurable goals. From a research standpoint, future investigations into FC and similar phenomena should focus less on the prospects of users' autonomous communicative contribution, and more on the possibilities of their developmental progression using this type of touch-based assistance.

CHAPTER 4 – TOUCH MAY REDUCE COGNITIVE LOAD DURING ASSISTED TYPING BY INDIVIDUALS WITH DEVELOPMENTAL DISABILITIES[2]

4.1 Introduction

In chapter 2 and 3, we have shown that it is possible for users with DD to participate in the generation of linguistic content within an FC dynamic. In particular, we proposed that FC can be a conduit for the development of linguistic and literacy skills. In this perspective the FC dynamic can be seen as the results of multiple components: ideomotor influence, linguistic scaffolding, and touch-based support.

In this chapter, we will propose a neurophysiological pathway by which touch based support might assist linguistic production, the touch signal reducing the cognitive load of postural and task-related sensorimotor coordination, freeing up cognitive resources for linguistic content generation.

The results presented in chapter 2 and 3 showed that the FC process is best studied as a collaborative effort (Sartori and Betti, 2015; Curioni et al., 2019). Thus, considered as a possible conduit for a collaboration, supported typing methods present a more complex and nuanced picture than the apparent consensus discrediting them would suggest. In this perspective, it would be of interest to investigate whether there are neurophysiological pathways by which physically supporting people with DD such as Autism (ASD) or Down Syndrome (DS) could enable them to co-create textual output that they could not generate and express independently. It is possible that supporting the user by touch may reduce the cognitive and sensorimotor load of generating content and interacting with communication interfaces. Consideration of this possibility requires a thorough analysis of the computational challenges faced by individuals with a range of DD and whether or how supportive touch might ease them. The literature on supporting typing methods has not attempted this, and so doing this is a key purpose of this chapter.

Typing is a complex skill that requires the coordination of multiple concurrent tasks. Typing while seated requires coordination of repeated reaching movements of the arm. The programming of these movements depends on postural control mechanisms that maintain a stable upright stance and counteract the mechanical perturbations produced by arm extensions (Section 4.2.1.1). Postural control involves the integration of vestibular, somatosensory, and visual information, which in turn loads the executive function (EF) system (Section 4.2.1.3). EF broadly refers to regulatory mechanisms that oversee goal-directed cognitive and motor processes by maintaining, and operating upon, task-relevant information (Baddeley, 1996; D'Esposito et al., 1999). Unifactorial models of EF attribute the roles of coordinating and regulating cognitive processes to a unique function, namely

[2] The work presented in this chapter is also reported in the published paper: Nicoli, G., Mitra, S., Pavon, G., Grayson, A., and Emerson, A. (2023a). Touch may reduce cognitive load during assisted typing by individuals with developmental disabilities. *Frontiers in Integrative Neuroscience*.

working memory or attentional control (Posner, 1980; Shallice and Burgess, 1991; Demetriou et al., 2019), whereas multifactor models distinguish between discrete, independent components (Diamond, 2013). Although the structure and unity of EF continue to be debated, it is generally agreed that EF is comprised of working memory, updating information held in working memory, mental flexibility (i.e., shifting between tasks or task sets), fluency, response inhibition, inhibition of task-irrelevant information, planning, problem-solving and self-monitoring (Miyake et al., 2000; Miyake and Friedman, 2012; Demetriou et al., 2019). See Section 6 and Table 1 for EFs relevant to the seated typing task.

The generation of the linguistic content to be typed places its own demands on EF (Section 4.2.2) and planning the movement sequence required to type out that content also comes with its own EF load (Section 4.2.1.2 and Section 4.2.1.3). The concurrent demands of sensorimotor coordination and cognitive tasks on common computing resources (resulting in interference in some conditions) has been extensively researched in the past few decades, particularly in the context of ageing (Section 4.3). The literature has also documented the beneficial impact an external somatosensory signal can have on postural control. The possibility we present here is that supportive touch might reduce the computational workload of generating and typing linguistic content by assisting the sensorimotor processes of typing (Section 4.4). Given the noted interactions between such sensorimotor and concurrent cognitive processes, tactile support has the possibility of freeing up cognitive capacity for the required linguistic effort. This prospect is considered in the context of extensive evidence that a range of DD affect both motor coordination and cognitive capacity. As we expand in Sections 4.5 and 4.6, individuals with DD experience sensorimotor deficits that affect both motor coordination and cognitive capacity. Sensorimotor deficits include impairments in sensory integration, postural control, and difficulties in planning and controlling voluntary movements. These deficits, combined with weakened trunk stability and impaired sensory integration, can make it challenging for individuals with DD to maintain a stable seated position and perform the precise arm movements required for typing. Furthermore, individuals with DD often experience executive function (EF) deficits, which may impact cognitive processes involved in typing, such as working memory, planning, flexibility, and inhibition. Thus, acknowledging the simultaneous presence of sensorimotor and EF deficits in DD populations sets the context for interpreting and implementing interventions such as light touch that be effective primarily by reducing the workload associated with the sensorimotor component.

In Section 2, we start providing a detailed analysis of what typing while sitting requires from a sensorimotor and cognitive perspective. Here, we also show how the associated sensorimotor and linguistic actions significantly draw on EFs. In Section 4.3, we present the literature on cognitive-motor interaction (CMI) that shows how concurrent motor, and cognitive tasks can interfere due to shared cognitive resources. In Section 4, we present the literature on the role that touch can play in aiding postural control, thereby reducing cognitive load. In Section 4.5, we establish the relationship between DD and sensorimotor deficits, and then, in Section 4.6, we demonstrate how a range of DD limit EF capacity. In Section 4.7, we synthesise the assembled information in support of the proposal that touch-based physical support may facilitate typed communication by individuals with DD by reducing the computational load of the sensorimotor and cognitive components of the task.

4.2 Task analysis

As typing is a complex task that involves both sensorimotor and cognitive components, in this section we analyse each component in turn, with a particular focus on how executing and coordinating these bear on the cognitive workload. We start with the sensorimotor coordination required for pointing gestures of the arm, and consider the cognitive processes involved in generating the linguistic content to be written.

4.2.1 Sensorimotor Coordination

The task of typing on a keyboard involves repeatedly aiming the typing fingertip at the required key and making a reaching movement toward the key. We assume that the key readily provides haptic and visual feedback when it is pressed. These sensory signals indicate goal achievement, and therefore the termination of the key press action.

Leaving aside the linguistic aspect, the action of typing requires the coordination of a postural task (setting the mechanical base) and a manual reaching task (pointing at the keyboard). The postural task stabilises the torso, and the torso's position and velocity affect the programming of the arm's reaching trajectory (Thelen and Spencer, 1998). To better understand the latter task's dependence on the former, we must examine the information requirements of both task components.

4.2.1.1 Mechanical base

The informational support for maintaining the body's upright stance comes from the integration of perceptual data processed by vestibular, somatosensory (cutaneous, proprioceptive, and joint receptors) and visual systems (Allum and Keshner, 1984; Diener et al., 1988; Shumway-Cook and Woollacott, 2012). The vestibular system provides information about the head's movement with respect to gravity and inertial forces (Horak et al., 1994). The somatosensory system provides information about the body's position and motion with respect to support surfaces and about the dynamic inter-relationship between body segments (Diener et al., 1984; Roll and Roll, 1988). The role of vision is to provide information about the position and motion of the head relative to environmental objects and a sense of verticality. Visual information is particularly salient in the detection of self-motion as movements of the head through a visible environment generate flows of optical elements across the entire visual field (Lee and Lishman, 1975; Dijkstra et al., 1992). Anterior-posterior head motion produces radial optical flow whereas medial-lateral head motion generates lamellar flow (Warren, 2010). When these visual signals are available, the body sways less in both planes (Edwards, 1946; Paulus et al., 1984, 1989). Indeed, the ratio of body sway between eyes-open and eyes-closed conditions, the Romberg quotient, is a clinical indicator of postural stability (Romberg, 1853). Research suggests that the maintenance of balance (for example, keeping the body's centre of mass within the base of support) involves both exploratory and corrective body sway. Exploratory sway generates perceptual information (including optical flow) that guides the compensatory sway that corrects drifts towards instability (Riccio et al., 1993; Riley et al., 1997). Although visual information is not essential for maintaining balance, it plays a dominant role when it is available and provides a strong signal of head motion. For example, when the train in the next track moves off, standing passengers in a static train produce a postural reaction consistent with their own train setting off. This happens despite the absence of any self-motion signals from their vestibular and somatosensory systems. In upright position, body sway is lower in the presence of vision, a result commonly interpreted as indicating greater stability (Andersen and Dyre, 1989; Masson et al., 1995). The closer the environmental objects on which the eyes fixate, the less the body sways (Lee and Lishman, 1975; Dijkstra et al., 1992). As the optical flow produced by nearer objects is larger in magnitude, this suggests that optical flow information is actively used to maintain stance stability.

In the typing task context, the posture control system has a dual function: a stabilising function in maintaining upright stance in the seated position, and a task-facilitative (Stoffregen et al., 2000) function that: (a) controls the position of the mechanical base (shoulder) from which the arm extension is parameterised, (b) contributes to the reaching action by controlling forward lean, and (c) anticipates and adapts to the perturbation generated by arm extension. The direction and amplitude of the reaching gesture appear to be prepared before movement begins, and, for this to be possible, information about the initial position of the limb is important (Polit and Bizzi, 1979). The position of the shoulder at the start of each reaching trajectory is the result of the facilitatory and stabilising functions of the posture control system. Both these functions are confirmed (in work on standing balance) by the activation of leg muscles during anticipatory postural adjustments before arm movement (Shepherd et al., 1993), and by the occurrence of earlier and larger postural adjustments reaching distance increases and the support area shrinks (Moore et al., 1992). With regard to planning the direction of pointing movements, there is considerable evidence that the trajectories are planned in spatial coordinates (Tresilian, 2012; Bosco et al., 2017). How this operates is addressed in the next section, but here it is important to note that the development of an internal coordinate system, be it head-, hand- or body-centred, requires a reliable and stable origin for reference. The observer's posture can influence the spatial relationships between objects in their visual field and can also affect their ability to perceive depth and movement. Additionally, changes in posture can alter the visual cues that are used to perceive the environment, such as the relative size and position of objects. Body sway, which refers to the small movements of the body caused by changes in balance and weight distribution, can have an impact on the visual coordinate system by altering the relative positions and orientations of the observer and the objects in their visual field (Thelen and Spencer, 1998). This section discussed the sensorimotor functions of maintaining an upright stance that is stable and able to support the motor functions of the task at hand. The next section outlines the components of arm trajectory planning in a task like typing.

4.2.1.2 Motor Planning

The first element of planning the trajectory of the fingertip (the working point) to the required key is visually locating the target key (termed 'visual regard'). This involves coordination of the trunk, head, and eyes (note that all three are also involved simultaneously in postural control). Forming the trajectory involves a differencing mechanism that compares the working point's current position to its required position. This internal feedback signal (internal to the trajectory generator) is used integratively to drive the current position of the working point to its target location (Saltzman and Kelso, 1987; Bullock et al., 1993; Hoff and Arbib, 1993). This process is one of negative feedback control and requires at least intermittent sampling of visual and proprioceptive information about the working point's current and required position in space. A differencing mechanism like this can only operate accurately if both the current and required positions are represented in the same coordinate system. These locations in space could be monitored in a coordinate system located at the visual egocenter (Tresilian, 2012), but it has been suggested that the coordinate system is centred on the point in the visual field where the eyes are fixating (Shadmehr and Wise, 2005). As this makes eye fixation fundamentally important to trajectory planning, we recall that it also affects the sampling of optic flow from eye-head motion and proprioceptive information from ocular vergence for use in postural control.

Aside from feedback-based closed loop control, fast movements also exhibit open loop control in which the trajectory is specified without feedback at execution time (Adams, 1971). Both these types of control have also been suggested for postural control (Collins and De Luca, 1993). Most reaching movements exhibit a hybrid control pattern whereby open loop control takes the working point close to the target location. Then, a set of sub-movements controlled in closed loop brings the working point precisely to the target location (Meyer et al., 1988). Accurate open-loop control is only possible if the consequences of motor commands can be estimated in advance. This implies access to detailed information about the articulatory apparatus. This process operates in a feedforward manner, utilising predictions of the results of motor commands and preparing elements of the controlled system for the resulting changes in their states (Pisotta and Molinari, 2014). The need for system knowledge also emerges when considering the transformation of spatial trajectory information to the required angular motion of the body's joints (inverse kinematics) and the muscle activity required to achieve these. Predictions of the sensory consequences of planned motor commands are termed forward models (Miall and Wolpert, 1996).

4.2.1.3 Executive function load of sensorimotor coordination

Research agrees that there is a cognitive workload associated with balance, gait, or other goal-directed sensorimotor coordination. In many situations, performing these tasks concurrently with other cognitive tasks can pose significant challenges. This may be due to capacity-limited cognitive resources being shared by both types of tasks (Mitra, 2004) or because tasks are functionally linked in terms of performance or system requirements (Stoffregen et al., 2007). Maintaining the body's balance is the key imperative for postural control, but posture and gait are constantly modulated in service of supra-postural tasks. The latter function of the posture control system is likely more demanding of cognitive resources than simply retaining balance as it must link and adapt coordination to specific and transient task goals.

As seen in the previous section, keeping an upright stance is the result of sensory and motor processes. Sensory processes compute the position of the body in space, motor processes allow for muscle and movement adaptation and responses to the detected position. The sensory processes rely on the integration of visual, vestibular and proprioceptive sensory information. The information provided by each of these channels is then weighted to give precedence according to reliability (Shumway-Cook and Horak, 1986). The literature clearly shows that the integration of sensory information poses demands on cognitive resources, so that decreased postural control, due to injury, aging or sensorimotor deficits (Fournier et al., 2014) increases the demands for attentional resources to maintain the body's balance. When information provided by one of the sensory channels deteriorates, the demands for attentional resources to deal with postural tasks increases (Shumway-Cook and Woollacott, 2000; Mahboobin et al., 2007). A striking implication of these studies is that adding reliable sensory information may substantially decrease the demands for executive resources that can then be allocated elsewhere. Thus, given the essential role of posture control in the execution of supra-postural tasks, by extension, multisensory integration also plays a decisive role in the planning and execution of movements (Betti et al., 2021). Motor planning itself draws on executive and cognitive resources. It has been proposed that motor planning and executive functions are two distinct heterogeneous domains of cognitive functioning (Wunsch et al., 2016), but many studies have reported dual-task interactions between motor planning and (visuo-spatial) working memory with detrimental effect on the latter (Schütz and Schack, 2020). Deficits in motor planning and execution, reported in many DD (Mari et al., 2003; Cummins et al., 2015; Alesi and Battaglia, 2019; Studenka and Myers, 2020), would therefore pose increased demands on the executive/cognitive domain.

The internal models involved in motor task execution are the suggested means of several important functions in motor control. These include motor learning, separating the effects of self-motion from sensory input, and counteracting the impact of delays in neural signal transmission (Miall and

Wolpert, 1996; Wolpert and Kawato, 1998). In terms of neural mechanisms, the planning and execution of reaching arm movements involves the parietal and premotor areas in spatial planning, the primary motor cortex and descending pathways in the activation of muscle groups, and the basal ganglia and cerebellum in refining the process by accounting for the current and predicted states of the body (Shumway-Cook and Woollacott, 2012). The cerebellum is thought to be involved in the use of both inverse models (providing the neural commands required for a given trajectory) and forward models predicting sensory consequences of actions (Wolpert et al., 1998). Wolpert and Kawato (1998) suggest that multiple pairs of forward and inverse models need to be trained during the acquisition of motor skills such that models suited to given task conditions can be activated, or control can be switched to better suited models if conditions change. Note that both selection and switching are EFs (Miyake et al., 2000).

As the reaching arm's position is critical in trajectory planning and depends on both the stabilising and task-facilitative roles of postural control, postural states and actions (e.g., of the torso) must be included in internal models of the kind of seated typing movements we are considering here (Wolpert and Kawato, 1998; Morasso et al., 1999; Kuo, 2005). A key point with respect to both limb movement and postural control is that much of it is anticipatory in nature. Whether responding to an expected external perturbation, or supporting a voluntary movement that perturbs balance, the required postural adjustments must be estimated and applied in advance. Evidence of this is seen not only in the case of executed movements (Belen'kiĭ et al., 1967; Bouisset and Zattara, 1988), but also in the case of motor imagery where only movement planning occurs but not execution (Wider et al., 2020; 2022). The close coordination that has been observed between anticipatory postural adjustments and associated limb movements (e.g., these adjustments can be affected independently by the magnitude of perturbation and magnitude of the action triggering the perturbation) has led to suggestions that anticipatory postural adjustments must be integral elements of limb movement planning (Aruin and Latash, 1995, 1996). As the limb movements themselves also involve anticipatory components within internal models, and anticipatory processes must involve choices based on task conditions and memory, the central importance of EFs in the selection, planning and execution of the seated typing movements we have been considering becomes evident.

This section established that sensorimotor coordination of both postural control and focal movement planning components of seated typing make significant demands on cognitive resources such as EFs. The next section considers the simultaneous EF demands of the content generation aspect of the seated typing task. Both these discussions should be taken in the context of EF deficits in DD that will be outlined in Section 6.

4.2.2 Generating written content

Writing is a problem-solving task (Cornoldi et al., 2010) that requires the coordination of multiple operational procedures working at central and peripheral levels (Ellis, 1982). In this section, we broadly describe the main processes involved in the generation of a written output with a particular focus on the demands these processes load on EF capacity.

4.2.2.1 Writing operations

The operational procedures involved in a writing task can be broadly divided into three recursive phases (Hayes and Flower, 1980). Models can vary in the number, name, and attribute of these phases. For present purposes, we present a broad summary. Note that while these processes are hierarchically ordered in a cascade-like model, their execution is intertwined in time (McCutchen, 2000; Cornoldi et al., 2010; Purcell et al., 2011). Thus, writing being a much slower task than talking, the processes that happen higher in the route (the generation of contents) may be expanded, modified, or updated during the completion of the lower (content's transcription). The first operational phase is the retrieval of semantic or contextual information and formulation of the ideas that need to be organised in text form (Hayes and Flower, 1980; Ellis, 1982; McCutchen, 2000; Cornoldi et al., 2010). This phase is constantly updated during the other phases of writing although an outline plan is needed in very first stages to allow the writing process to start (Cornoldi et al., 2010). The second phase translates into linguistic representations of the ideas generated in the first phase (Berninger, 1999; McCutchen, 2000; De Vita et al., 2021). This process can be itself split into two components: a text generation phase, where concepts are translated into lexical units and the broad text is organised into a syntactic plan, and a transcription phase where these linguistic representations are transformed into written words (Cornoldi et al., 2010; De Vita et al., 2021). The latter is composed by a central and a peripheral process. The central (spelling) process creates a graphemic and orthographic representation of the linguistic representation. The peripheral (motor) process realises graphemes through handwriting (graphomotor skills), typing (pointing gestures) or oral spelling (Ellis, 1982; De Vita et al., 2021). The third phase involves revising procedures, namely operations that check textual adequacy and linguistic features (Hayes and Flower, 1980; Berninger, 1999; Cornoldi et al., 2010).

4.2.2.2 Executive function load of writing

A writing task requires constant and recursive shifting between long-term memory retrieval (knowledge) and textual operations (processes), (Hayes and Flower, 1980; Cornoldi et al., 2010). The coordination of this multiple, hierarchically ordered, and intertwined operations are overseen and constrained by an executive system (Berninger, 1999; McCutchen, 2000). We have already referred to writing as a problem-solving task (problem solving is an EF, see section 6 for references), but inhibition, updating, planning, self-monitoring and working memory are also involved (Salas and Silvente, 2020; De Vita et al., 2021). Please refer to Table 4.1 for a summary of the EF involved in a writing task. Depending on the level of expertise, the constraints of EF are dealt with differently. Expert writers utilise much of their EF resources on idea generation, conceptual organisation, and retrieval of lexical and syntactic structures suited to the context and the goal of the task. They are also able to coordinate the revision process to both check orthographic, linguistic, and overall general textual aspect (Cornoldi et al., 2010). Less expert writers such as children devote much of their working memory resources to spelling and motor processes, as these operations are not yet automatised, resulting in less resources being available for semantic and linguistic planning (Berninger, 1999; McCutchen, 2000; Salas and Silvente, 2020; De Vita et al., 2021) and greater challenges in coordinating the revision of orthographic and linguistic features (Cornoldi et al., 2010).

Executive Function	**Description**
Inhibition	The ability to suppress irrelevant or distracting linguistic and non-linguistic information.
Updating	The capacity to continuously monitor and update information in working memory during the writing process. This involves integrating new ideas or information and modifying the written output accordingly.
Planning	The process of organizing and structuring the written content before typing. It includes developing an outline or framework for the text, deciding on the sequence of ideas, and formulating a plan for how to express those ideas effectively.
Self-monitoring	The ability to monitor one's own performance during typing, checking for errors, inconsistencies, or deviations from the intended message. It involves self-evaluation and making adjustments to improve the quality and accuracy of the written output.
Working memory	The capacity to hold and manipulate information in mind while performing cognitive tasks. In typing, working memory is involved in temporarily storing and retrieving relevant information, such as graphemic strings, vocabulary, grammar rules, and previously written content.
Problem solving	The cognitive ability to identify, analyse, and solve problems encountered during the writing process. It includes identifying the most appropriate words, phrases, or sentence structures to convey meaning effectively.
Motor planning and coordination	The coordination of motor movements required for typing, including the precise control of finger movements and keystrokes to accurately produce written words.

Table 4.1. Summary of the executive functions required during a typing task.

What clearly emerges from the literature on writing processes is that to perform successfully at a good level, cognitive resources have to be devoted to higher level operations (text generation, concept planning, lexical decision, morpho-syntactic organization, writing oversee and monitoring), rather than on lower ones (orthographic planning, motor execution). Struggling to derive an orthographic buffer from linguistic representations or else to coordinate translation into motor gestures of the output of the orthographic buffer would overload the working memory system with a detrimental effect on higher-ordered operations (Berninger, 1999; Cornoldi et al., 2010; Salas and Silvente, 2020; De Vita et al., 2021).

4.3 Cognitive motor interaction

Section 2 provided an analysis of the computational components of the task of seated typing. The load placed on EF by both the motor and linguistic production components was noted. This section summarises the extensive literature on interactions between motor coordination and concurrent cognitive tasks. The essential point it seeks to establish is that EF capacity can be a limiting factor in the success of cognitive-motor dual tasks. Seated typing is, of course, a clear instance of this type of dual task.

It is increasingly clear that sensorimotor coordination involved in posture and gait control, not to mention the planning and execution of voluntary goal-directed movement, draws significantly and continuously on EF resources (Fraizer and Mitra, 2008b; Al-Yahya et al., 2011; Amboni et al., 2013). This understanding arose initially in research on the effects of ageing on balance and gait control. Ageing is associated with both reduced EF capacity (Fisk and Sharp, 2004; Clarys et al., 2009) and increased involvement of higher-level cognitive processes in motor coordination (for example, increased reliance on visual feedback) (Lajoie et al., 1996; Peper et al., 2012; Yeh et al., 2014; Hollands et al., 2017). A large body of dual-tasking research has shown that adding attention and EF load to ongoing balancing or gait tasks affects performance in either or both tasks (Li and Lindenberger, 2002; Woollacott and Shumway-Cook, 2002; Fraizer and Mitra, 2008a; Al-Yahya et al., 2011). Such dual-task interactions have been found not only in older people and neurological patients, but also in healthy young adults. This suggests that these cognitive motor interaction effects do not arise from the EF capacity and sensorimotor performance deficits associated with old age (or neurological conditions) but are largely amplified by them.

Several theoretical frameworks have been used to explain the complex results obtained across studies of cognitive-motor interaction. The most commonly adopted framework accepts that there is some involvement of high-level cognitive function in posture and gait control (Tresilian, 2012), and cognitive-motor dual-task interactions arise because both types of tasks engage common mechanisms. Drawing on classic attention theory (Broadbent, 1958), the bottleneck version of this account suggests that cognitive-motor interaction results from the sharing of a serial processor between cognitive and motor operations (Pashler, 1994; Meyer and Kieras, 1997; Tombu and

Jolicoeur, 2003; Bayot et al., 2018). Operations that utilise the same neural pathway or network must take turns. The bottleneck account has two variants, structural and strategic (Bayot et al., 2018). The former suggests that the processor generates a bottleneck effect at the decision-making stage, whereas the latter postulates that the same interference happens at the response-control stage or at a peripheral level when tasks share the same input or output processors. The capacity or resource sharing model (Tombu and Jolicoeur, 2003; Mitra, 2004; Bayot et al., 2018) posits that a finite pool of processing resources must be shared by concurrent task operations. If the resource draw of one task increases, a deficit in resourcing the other emerges. Accordingly, older people in particular have been shown to operate a 'posture first' principle (Shumway-Cook et al., 1997) whereby they prioritise the balancing task by discontinuing a concurrent cognitive task when they detect a risk of balance failure. Some accounts postulate multiple resource pools specific to particular types of operation (e.g., spatial processing) such that interactions occur when cognitive and balancing tasks place demands on the same type of processing resource (Navon and Gopher, 1979; Bayot et al., 2018).

In cognitive-motor interaction research, motor performance is commonly evaluated using speed, cadence, or stride time to assess gait, or centre-of-pressure (the point of application of ground reaction force) displacement and frequency to measure body sway to assess postural control (Fraizer and Mitra, 2008a; Al-Yahya et al., 2011). Slower gait speed, reduced cadence, or increased body sway are taken to indicate a deterioration in motor performance. A wide range of cognitive tasks including working memory, verbal fluency, inhibition, set-shifting and arithmetic skills, most involving EF, have been studied using behavioural performance indicators such as response time and accuracy, and, more recently, at the neurophysiological level using electrophysiology (Reiser et al., 2020; Swerdloff and Hargrove, 2020).

Despite variability in outcomes, sometimes due to methodological differences (Fraizer and Mitra, 2008a; Bayot et al., 2018), research has tended to show that concurrent EF tasks result in performance deficits in balance and gait in older people (Shumway-Cook et al., 1997; Morris et al., 2000; Swanenburg et al., 2009; Chang et al., 2010; Nadkarni et al., 2010; Al-Yahya et al., 2011; Patel et al., 2014; Fernandes et al., 2015; Bahureksa et al., 2017; Hsiu-Chen et al., 2020; Morenilla et al., 2020; Przysucha et al., 2020; Varas-Diaz et al., 2020). Similar results have been reported in stroke patients (Lee et al., 2020) and, importantly, also in young adults (Dault et al., 2001; Woollacott and Shumway-Cook, 2002; Pellecchia, 2003; Nadkarni et al., 2010; Onofrei et al., 2020) and children (Chang et al., 2010; Bucci et al., 2013; Palluel et al., 2019). The literature also describes executive task performance deficits when body posture is perturbed or motor task complexity increases (Andersson et al., 1998, 2002; Brown et al., 1999; Yardley et al., 2001; Wollesen et al., 2016; Estevan et al., 2018; Abou Khalil et al., 2020; Reiser et al., 2020; Stephenson et al., 2020; Swerdloff and Hargrove, 2020). These results appear to provide clear evidence that the coordination of balance or gait has an EF load associated with it. A reduction in available EF resources negatively affects coordination, and impaired coordination adds to EF load.

Although the results of cognitive-motor dual tasking are most often interpreted as patterns of mutual interference, in some situations, there are reasons to be wary about such conclusions (and the theories they are taken to support). When adding a concurrent sensorimotor task, the accuracy of a cognitive task is reduced, or the response time increases, it would appear clearly that dual tasking negatively impacted cognitive task performance. Where the sensorimotor task is simply maintaining upright stance, the effect of a concurrent task is measured as a change in body sway. Commonly, increased sway is interpreted as a negative effect on postural stabilisation functions. By this logic, reduced body sway would indicate improved stability. Although commonly applied, this logic does not adequately explain all empirical data. Posture-cognition dual task studies have reported both increased and reduced body sway when performing concurrent cognitive tasks (Fraizer and Mitra, 2008a). It is also doubtful that the posture control system always cares to reduce body sway to increase stance stability beyond simply ensuring that the centre of gravity stays within the base of support (Stoffregen et al., 1999). If so, a change in body sway may indicate an imperative other than improving stance stability. The logic also fails where the secondary task engages the posture control system in facilitative actions other than, and even in opposition to, maximising stance stability (Stoffregen et al., 1999). If the secondary task requires precise eye fixations for reading, for example, body sway might be reduced, not because reading impedes the posture control system's stability maintenance function, but because postural control acts to stabilise the head to aid reading (Stoffregen et al., 2000). Such considerations underpin an alternative view of posture-cognition dual tasking that points to functional linkages (such as the shared use of vision) rather than a competition for cognitive resources as the mechanism of interaction (Stoffregen et al., 2007). This approach also emphasises the fact that postural control in everyday life is almost always organised to enable some supra-postural tasks rather than simply to maximise stance stability. Thus, postural control is itself a multi-task function charged with maintaining stance as well as facilitating supra-postural tasks.

Many of the ambiguities about the effects of cognitive load on motor tasks arise in laboratory studies of dual tasking in which the postural task is simply to maintain upright stance. In some situations, the cognitive task clearly uses a function that postural control also uses, for example, when the cognitive task requires visual perception and attention that are also required by a balancing task. But in other cases, the cognitive task has no obvious sensorimotor component. Interaction effects have been reported in both cases, but their consistency and size under the latter conditions have been questioned (Stoffregen et al., 2007). Using the results of dual task studies to draw conclusions about the role of cognition in the control of quiet standing may not be straightforward, but the effect of concurrent cognitive load is more clearly detrimental when counteracting perturbations to body posture (Fraizer and Mitra, 2008a). There is considerable evidence of cortical involvement in shaping responses to postural perturbation, including the modulation of postural response based on cognitive state, sensorimotor conditions and past experience (Jacobs and Horak, 2007; Jacobs, 2014; Bolton, 2015; Peterson et al., 2016; Ghosn et al., 2020). Switching attention (an EF) to balancing function is a key aspect of responding to perturbation (Maki et al., 2001). Concurrently performing EF tasks (e.g., mental arithmetic) reduces the amplitude of postural muscle activity (though not its latency) when responding to perturbation (Rankin et al., 2000). Analogously, when attention is engaged in a tracking task during postural perturbation, the magnitude (but not the latency) of the cortical response, detected electrophysiologically as the N1 potential (Adkin et al., 2008), is attenuated (Quant et al., 2004). Deterioration in EF predicts loss of balance in older individuals (Buracchio et al., 2011; Kearney et al., 2013) and concurrent performance of EF tasks affects a number of gait measures (Al-Yahya et al., 2011). In the case of gait, the prefrontal cortex is known to become involved when the coordination needs to adapt to changing task requirements (e.g., a change of speed or a transition to running) (Suzuki et al., 2004), suggesting a role for EF in tailoring coordination to task goals.

The effects of concurrent cognitive load become even clearer when the motor task includes aimed movements of the upper limb as everyday tasks like driving (Strayer and Johnston, 2001; Recarte and Nunes, 2003). Pursuit-tracking tasks have a long history of use in dual-task interactions (Isreal et al., 1980; Kramer et al., 1983; Brown, 1998; Gazes et al., 2010), including as a simulated driving task (Strayer and Johnston, 2001) and as a secondary task during postural perturbations (Mcilroy et al., 1999; Norrie et al., 2002). Baker et al. (2018) monitored the electrophysiological correlates of detecting and tallying the occurrence of visual oddball stimuli while performing a visuomanual tracking task. They found that adding the tracking task attenuated the markers of attentional (but not perceptual) processes even though tracking task performance was itself unaffected by the oddball task at these timescales. Tracking performance did suffer when, after detecting an oddball, the target tally was updated (updating is recognised as an EF). This demonstrates that cognitive-motor dual task interactions can have intricate mechanisms composed of separate, asymmetric and asynchronous influences between tasks.

For present purposes, the key message from this research is that there is a cognitive workload associated with balance, gait, or other goal-directed sensorimotor coordination. In many situations, performing these tasks concurrently with other cognitive tasks can pose significant challenges. This may be due to capacity-limited EF resources being shared by both types of tasks, or because task pairs are functionally linked in terms of performance requirements. Maintaining the body's balance is the key imperative for postural control, but posture and gait are constantly modulated in service of supra-postural tasks. The latter function of the posture control system is likely more demanding of cognitive resources than simply retaining balance as it must link and adapt coordination to specific and transient task goals. These considerations support our present focus on the potential benefits of facilitating motor coordination as a means of easing the combined workload faced by individuals with DD when they perform sensorimotor – cognitive dual tasks as typing.

4.4 The utility of touch information in balance control

As shown by the previous chapters, a number of techniques seek to assist individuals with DD to type text on a keyboard or to point to textual or pictorial information on a screen by providing them with supportive touch on the torso or arm (Lilienfeld et al., 2014; Schlosser et al., 2014; Beals, 2022). Critics of these systems have pointed out that touch information can serve to cue the typing actions (Wegner et al., 2003; Mostert, 2010; Saloviita, 2018) in an ideomotor hypothesis perspective. The results provided in chapters 2 and 3, however has shown that Facilitated Communication cannot be interpreted uniquely in terms of facilitators' ideomotor influence. The literature on supported typing has not considered the possibility that, different from specific action-cuing, an external touch signal can aid postural control and thereby reduce the overall computational workload of the typing task.

The role of touch in balancing has been investigated in detail in the context of balance challenges due to ageing (Jeka, 1997; Johannsen et al., 2009; Rabin et al., 2013; Ditthaphongphakdee and Gaogasigam, 2020), stroke (Lee et al., 2018, 2020; Martinelli et al., 2018), blindness (Jeka et al., 1996; Schieppati et al., 2014) and childhood DD (Baldan et al., 2014; Chen and Tsai, 2015; Chen et al., 2019). The benefits of light touch in balancing have also been demonstrated in healthy young adults (Krishnamoorthy et al., 2002; Magalhães and Kohn, 2011; Martinelli et al., 2018; Kaulmann et al., 2020), but its impact becomes greater in the context of motor and postural difficulties due to disability or ageing (Baldan et al., 2014). Early research on this showed that light touch (< 1N of force applied) can improve postural stability (as indicated by reduced body sway) and reduce falling risk (Holden et al., 1994; Jeka and Lackner, 1994, 1995; Jeka, 1997). Noteworthily, the provision of an haptic feedback have also proven to be efficient in reducing trunk postural sway in a seating position (Maaswinkel et al., 2014). Light touch does not support the body's weight but aids postural control by providing an external somatosensory reference for judging body motion (Jeka and Lackner, 1995; Riley et al., 1997). The touched object need not even remain static against the applied force. Lightly touching a hanging curtain can replace the level of reduction in body sway that the availability of vision provides (Riley et al., 1999). Indeed, light touch can be as effective as forceful touch in stabilizing body sway by providing information to guide anticipatory muscle activation (Jeka and Lackner, 1994). Importantly for present purposes, research shows that postural assistance by touch works whether the touching is active (for example, the assisted person touches the external surface) or passive (for example, another individual or a mechanical arm lightly touches the individual on the back or shoulder)(Johannsen et al., 2009, 2011).

Light touch can also reduce postural instability arising from to a concurrent cognitive task (Lee et al., 2018, 2020) suggesting that light touch may reduce the overall cognitive workload of cognitive-motor dual tasking. Chen et al.(2015) showed, for example, that light touch to aid posture control resulted in improved performance in a concurrent visual search task. Such results suggest that light touch may play a particularly important role in reducing visual attention load during cognitive-motor dual tasking. In this context, it is important to note that touch information can be used by the posture control system to facilitate a supra-postural task such as visual search, as in the case of Chen et al. (2015), and maintenance of the light touch itself, as in the case of Riley et al. (1999). The latter study found reduced postural sway only when precisely touching a hanging curtain was an actual task goal. For present purposes, the point is that touch information can reduce the total workload of a seated typing task, potentially by assisting the maintenance of upright stance, or by facilitating the postural component of planning and executing the repeated reaching movements of the typing arm. To the extent that these coordination tasks involve EF, reducing their workload has the potential to release resources for the message formulation (as lexical choices, morpho-syntactical planning) and sequencing functions involved in typed communication. Section 4 presented the details of the visual system's dual role in the maintenance of postural stability and in postural facilitation of other tasks. This background now enables us to appreciate, in the context of assisted typing, the potentially key role of a touch signal in reducing the demands placed on the visual system by postural control. This could free up visual processing resources that are simultaneously demanded by the planning and execution of typing the required sequence of key presses.

In summary, the literature shows that light touch can facilitate a posture-cognition dual task by providing a reference signal that assists postural control and therefore lowers the overall workload of the task combination. With respect to assisted typing techniques as FC, it could be argued that light touch provided by an inanimate object, or by the backseat of the chair, should also be facilitative. Indeed, a successful case has been reported of assisted typing with a mechanical arm facilitating the arm gestures towards the keyboard (Oudin et al., 2007). It should be noted that the robotic arm in that case was developed to counteract movement perseverations and so the touch applied to the arm was far from light. Also, comparing robotic and human assistance showed a prominent superiority of the latter. One property of a light touch applied by a human facilitator in assisted typing is that the touch can be maintained across the postural changes associated with typing (leaning towards and back from the keyboard, lateral torso movements in sympathy with the typing arm's movement across the keyboard). This allows the touch signal to be both present and lightly modulated by the typist's torso movements, serving as feedback about the movements. Any system that allows maintaining and modulating a tactile reference in this way should theoretically also reduce the cognitive effort of the sensorimotor control task.

4.5 Sensorimotor deficits in DD

The direct effect of any touch-based assistance in the seated typing task is likely to be on sensorimotor coordination. The etiology of the sensorimotor deficits will not be the same across DDs. Even so, if a touch signal could function as a supplementary sensory aid to postural control, it could contribute to reducing the overall cognitive workload of individuals with a range of DDs with associated sensorimotor deficits. This section summarises the literature on the sensorimotor deficits that accompany a range of DD, with a particular focus on ASD and DS populations. The goal is to note the impact of these sensorimotor deficits on the seated typing task.

Sensorimotor deficits refer to broad impairments in the integration of sensory information that orientate and control motor tasks (Coll et al., 2020). Children and adolescents with sensorimotor deficits show prominent postural and gait deficits along with difficulty in planning and controlling voluntary movements (Damasio and Maurer, 1978; Webber et al., 2004; Galli et al., 2008, 2011; Torres, 2013b; Bieć et al., 2014; Fournier et al., 2014; O'Keefe et al., 2016; Lim et al., 2017; Klotzbier et al., 2020).

For individuals with DS, impaired postural control, and equilibrium, as well as weaknesses in head control and trunk stability, can disrupt the proprioceptive system and hinder sensory integration (Uyanik et al., 2003; Georgescu et al., 2016; Jain et al., 2022). These difficulties in maintaining stable posture and coordinating movements can directly impact the ability to sit comfortably and maintain the necessary balance required for typing. The hypotonicity often experienced by individuals with DS may further compound these challenges, making it more difficult to maintain an upright sitting position and stabilize the arms for precise typing gestures.

Similarly, the ASD literature has recently seen the emergence of a motor perspective (Torres and Donnellan, 2015b) that acknowledges not only the significant presence of sensorimotor coordination deficits, but also that these might be core features in the characterization of ASD. Individuals with ASD frequently experience sensorimotor coordination deficits, including postural instability, poor task-oriented coordination, and movement planning difficulties (Frith et al., 2003; Mari et al., 2003; Fournier et al., 2014; Arabameri and Sotoodeh, 2015; Mache and Todd, 2016; Lim et al., 2017; Begum Ali et al., 2020). These deficits can affect their ability to sit with stability and perform the coordinated arm movements required for typing. Difficulties in sensory integration, such as integrating visual, vestibular, and proprioceptive information, further contribute to the challenges faced by individuals with ASD when engaging in tasks that demand postural balance and precise arm control (Memari et al., 2013; Doumas et al., 2016). For present purposes, it is noteworthy that cognitive performance and muscle strength have been shown to be related in people with ASD, with higher muscular strength associated with increased cognitive performance (Ludyga et al., 2021).

The seemingly simple task of sitting and typing can pose significant challenges for individuals with DD such as DS or ASD. With regard to DS and ASD, the vast majority of postural studies has focused on impairments in standing balance and gait rather than sitting. Most of the research focusing on sitting while balancing has been done on infants and children with DS and ASD. Broadly, the results show delayed acquisition of the sitting stance and lack of balance control associated with the sitting position in both populations (Connolly and Michael, 1986; Lauteslager et al., 1998; Minshew et al., 2004; Czermainski et al., 2014; Semrud-Clikeman et al., 2014; Arabameri and Sotoodeh, 2015; Marchal et al., 2016; Leezenbaum and Iverson, 2019; Jain et al., 2022).

Maintaining an upright seated position may be an easier task than standing or walking, but it still requires the integration of sensorimotor information (Genthon and Rougier, 2006; Maaswinkel et al., 2014; Serra-AÑó et al., 2015). Moreover, typing while sitting significantly perturbs upright posture by requiring the typing arm to repeatedly cross the midline, and visual fixation to continuously shift around the keyboard (Kaminski et al., 1995). Thus, the sensorimotor deficits in DS and ASD also impact the perturbed sitting posture required by a typing task (Tsimaras and Fotiadou, 2004; Salar et al., 2014). Trunk stability is an essential component of seated balancing (Genthon and Rougier, 2006; Maaswinkel et al., 2014; Roberts and Vette, 2019). The absence of proprioceptive information from legs and ankles joints makes the trunk primarily responsible of maintaining a balanced upright position (Genthon and Rougier, 2006). The literature indicates that both the DS and ASD populations may have weakened trunk muscular strength and challenging balance while sitting (Kohen-Raz, 1981; Weiss et al., 2013; Salar et al., 2014; Ghaeeni et al., 2015; Aly and Abonour, 2016; Salar and Daneshmandi, 2016; Jain et al., 2022) .

Postural and motor coordination deficits in DD are generally associated with disrupted sensorimotor integration which results in difficulties when sensory information load increases (Uyanik et al., 2003; Memari et al., 2013; Doumas et al., 2016; Georgescu et al., 2016; Mache and Todd, 2016; O'Keefe et al., 2016). Difficulties in these domains have adverse consequences in everyday life that affect the execution of daily activities, the development of motor and social skills, and, ultimately, independent functioning (Memari et al., 2013; Lim et al., 2017).

As in the case of EF (see Section 6), it is important to note that similar sensorimotor deficits may have different etiology in different conditions. In the case of ASD, sensorimotor deficits have been attributed to a general disruption in sensorimotor integration due to cerebellar problems and reduced Purkinje cell numbers (Doumas et al., 2016), impaired cerebellum and basal ganglia (Memari et al., 2013), or dysfunctions of multi synaptic pathways in the brain (Molloy et al., 2003). Regarding DS, sensorimotor deficits are generally attributed to hypotonia, ligament laxity and inherent musculoskeletal characteristics (Galli et al., 2008; Wang et al., 2012; Bieć et al., 2014; Klotzbier et al., 2020). According to some researchers, hypotonicity may disrupt feedback loops and affect the voluntary control of muscles (Georgescu et al., 2016). Uyanik (2003) has proposed that sensory integration dysfunction can be due to a reduced number of neural connections in the motor cortex, basal ganglia, and brain stem.

It is worth noting, that sensorimotor deficits have been described in many other DD. Increased body sway and postural instability have also been observed in different task conditions in young adults with Cerebral Palsy (Donker et al., 2008; Sæther et al., 2015) and Williams syndrome (Barozzi et al., 2013). Deficits in static and dynamic balance have also been reported in adults with Fragile X

Syndrome (O'Keefe et al., 2016). Furthermore, severe postural instability in children with Prader Willies and Ehlers Danlos syndromes have been documented (Galli et al., 2011). The existence of such similar traits in these different DD coincides with the use of assisted typing interventions in all these conditions.

In summary, for individuals with sensorimotor deficits, sitting and typing can be a complex and demanding task as the required coordination overlaps the sensorimotor impairments they experience. Impaired proprioception, weak trunk stability, and disrupted sensory integration highlight the need for tailored interventions to facilitate their engagement in activities requiring sitting and typing.

4.6 EF deficits in DD

As EF represents the core mechanism that directs cognitive resources in higher order mental tasks (Norman and Shallice, 1986; Baddeley, 1992; Royall et al., 2002), the role of EF deficits has received significant attention in the context of a range of DD including ASD-and DS (Lanfranchi et al., 2010; Hessl et al., 2019). For example, adolescents with DS show performance deficits in tasks involving working memory, planning, conceptual shifting, inhibition and set-shifting (Lanfranchi et al., 2010). There is an extensive literature on impairment of EF in the ASD population, especially in planning, flexibility, inhibition, auditory and visuospatial working memory, and verbal fluency (Robinson et al., 2009; Czermainski et al., 2014; Kercood et al., 2014). The distribution of cognitive resources (e.g., executive attention) is a key EF, therefore executive dysfunction would impact the allocation of cognitive resources that are limited in those cases where intellectual disability coexists with DD.

The presence of such executive dysfunction in DS, ASD and other DD connects closely with the seated typing task. The cognitive component associated with typing, (i.e., the generation of linguistic content) relies on EFs (see section 4.2) and Table 4.1, where we presented a list of EFs and their role in a typing task. Deficits in planning would limit the strategies available for organising the content to be typed (narrating an event, answering a question…), deficits in verbal fluency would impair finding the lexical target of a conceptual referent, and working memory impairment would influence typing effectiveness at the sentence and word level. People with executive dysfunctions may find it difficult to maintain the to-be-typed sentence, or even the graphemic string (this is crucial in one-finger typing systems as seen in assisted typing techniques). Similarly, EF dysfunction would also impact the execution of both the postural and focal motor task components of seated typing. These components include keeping the torso upright and stable and programming the sequence of typing movements. The latter requires visuo-spatial orientation to the letter targets on the keyboard and the inverse kinematics required to navigate the finger to the required key.

EF deficits in DD reduce the speed and effectiveness of linguistic content generation. Simultaneously, they impair the ability to stabilize the body and deploy the precise arm movements required for typing. Aside from adversely affecting both task components, reduced EF capacity also limits the ability to manage dual task demands by flexibly allocating and reallocating resources

(Mitra, 2004). The net effect would be slowed content generation, delays in motor execution and increased pressure on working memory as the expression of each narrative unit stretches out in time. It is worth noting again that EF deficits occur in a range of DD (Pennington and Ozonoff, 1996; Daunhauer and Fidler, 2013; Demetriou et al., 2018), but their etiology may be different in conditions such as Fragile-X, Cerebral Palsy and Williams Syndrome (Pennington and Ozonoff, 1996; Temple and Sanfilippo, 2003; Lanfranchi et al., 2010; Weierink et al., 2013; Hessl et al., 2019; Wotherspoon et al., 2023). In the case of the ASD, EF deficits have been linked to atypical network connectivity between the prefrontal and other cortical regions (Nomi and Uddin, 2015), or to dysfunctional coordination between the frontal lobe and the rest of the brain (Hill, 2004). In DS, it has been proposed that the co-occurrence of Obstructive Sleep Apnoea, and therefore an obstruction of the upper respiratory tract, may contribute to EF impairment as disrupted and fragmented sleep interferes with the maturation of the prefrontal cortex (Joyce et al., 2020).

4.7 General Discussion-Sequences of events

This chapter sought to present a possible neural pathway by which supportive touch might facilitate the seated typing task performed by individuals with DD. We showed that seated typing requires the coordination of intertwined sensorimotor and EF components. To type while seated, a person first needs the postural basis of a stable upright stance. Postural stability is achieved through the integration of multisensory information (vestibular, somatosensory, and visual). This invokes EF processes and contributes to the overall cognitive load of the typing task. Besides ensuring a stable stance, the postural system plays a facilitative role in the motor planning. Posture control positions the torso in space and in relation to the keys on the keyboard. Computation of the arm trajectories required to type the required key sequences depends on the position and velocity coordinates of the torso. Recent models suggest that multiple coordinate systems are involved in the integration of multisensory information gathered at eye-, head-, and body-centred levels. Even if the coordinates of the target key are computed at a visual level (eye-centred), a body-centred coordinate system is necessary to compute the position of the arm linked to the torso. Also, the usability of an eye-centred coordinate system depends on head stability which in turn is linked to torso stability. Reduced postural stability would increase the dynamic updating of arm trajectory parameters and add to the EF load of the whole task. Postural control therefore plays a crucial facilitative role in the planning and execution of typing actions. Besides planning the arm trajectories, postural control must also anticipate and counteract the perturbations that arise from repeated manual reaching.

In addition to controlling upright posture and coordinating the arm movement sequences, a seated typist also generates linguistic content to be typed. This is a problem-solving task that coordinates ideation and the process of converting ideas into linguistic form and graphemic representations. Together, these tasks are cognitively demanding as they required a constant shift between long-term memory (ideation) and working memory (processing). They also involve inhibition and updating processes that are key aspects of EF.

The typing task's sensorimotor and cognitive components are inter-linked and so place concurrent demands on the same cognitive resource pool. The challenges of this task are compounded in people with DD as both their sensorimotor coordination and EF are adversely affected. Multisensory integration capacity for postural stability and motor coordination is reduced, which in turn reduces the already lower level of EF capacity available for the linguistic aspects of the task. The summarised literature suggests that an assistive system that could reduce the cognitive load of postural control and motor planning and execution might free up cognitive resources for linguistic ideation and process. The literature also shows that a light external touch that is not load-bearing but provides an external reference signal can benefit postural control similarly to visual information. If external touch is provided at the level of the torso, as a hand on the shoulder, for example, it can facilitate the stabilisation of upright stance and free up visual processing resources. These resources can then be used in coordinating the typing task where visual fixation is involved in planning reaching movements of the arm, locating the symbols on the keys, and matching these to the contents of the orthographic buffer. If the external touch is provided through holding the arm, assistance for posture control may be greater as holding the hand could also counteract the postural perturbations that result from arm movement. However, this clearly increases the possibility of influence from the assistant. Other techniques like hand-over-hand assistance (Reichow, 2013), while clearly different in their goals from assisted typing techniques, may also exploit the reduction of cognitive and sensorimotor workload from the availability of touch. Indeed, if we are less concerned about the autonomy of content production and more interested in helping challenged individuals develop some literacy and typing skills, the possibilities of harnessing touch support can be seen in a different light.

In this chapter we have focused on the facilitative role of touch in the context of a typing task. This to propose a possible, underexplored, partial account for why FC and assisted typing techniques may work. However, the facilitative role of touch could also benefit the execution of tasks different from typing itself.

We have shown here that sensorimotor issues are core features of many DD, that these features are sensibly bearing on the mental workload and as such they interact with the execution of sensorimotor and cognitive tasks.

Typing is characterised by a complex and sequential pointing task. Here the sensorimotor task (visual research, arm coordination) and the low ordered linguistic process (graphemic buffer) are strictly intertwined in time and have to progress in parallel. The delay in processing one of the tasks directly affect the execution and the mental load of the other.

However, we have shown that postural and sensorimotor deficits interact with tasks that have lower motor coordination demands (other than maintaining posture or single pointing) and that the provision of light touch is similarly efficient in reducing the load of the tasks.

In this context, we propose that the provision of touch support to assist the execution of cognitive or sensorimotor task may deserve further exploration to inform other possible applications of haptic feedback support beyond the soles assisted typing techniques.

This chapter's argument is not that all the effects of touch in assisted typing are in the form of cognitive load reduction. The existence of the presented pathway for cognitive load reduction does not negate the possibility of specific cuing by the facilitator's touch. What it does is show that specific cuing is not the only plausible effect of touch on typing task performance. As noted in the outset, the arguments offered in the present chapter are developed from the position that assisted typing is a co-created and developmental process.

CHAPTER 5 - DOES THE PROVISION OF A HAPTIC FEEDBACK MODULATE DORSOLATERAL PREFRONTAL CORTEX ACTIVITY? AN FNIRS STDUY

Introduction 5.1

In chapter 4 we have proposed a theoretical hypothesis that can partially contribute to the description and explanation of touch based assisted typing techniques. Specifically, we proposed that people who face sensorimotor difficulties may benefit from the provision of a haptic support during the accomplishment of motor – cognitive dual task such as typing. The literature contains extensive evidence that concurrent sensorimotor and cognitive tasks compete for the same pool of cognitive resources (Teasdale et al., 1993; Al-Yahya et al., 2011). This competition can negatively impact one or both tasks especially when one of the two tasks posits a greater challenge. In the context of people with DD as well as in the ageing population, the literature shows that for these groups maintaining posture can be challenging especially when other mental tasks co-occur. These increased difficulties with sensorimotor tasks therefore call for the recruitment of more mental resources, therefore increasing the overall mental workload (Bieć et al., 2014; Fernandes et al., 2015; Miller et al., 2019). In the previous chapter, we referred to the literature on the light touch paradigm (Jeka, 1997; Clark et al., 2014; Chen et al., 2015). We proposed that the provision of a touch-based support can facilitate the execution of the co-occurrent postural task, freeing up cognitive resources for the co-occurrent cognitive task.

This chapter provides an initial empirical exploration of the theoretical hypothesis presented in Chapter 4. In particular, we investigated whether touch modulates the cognitive load associated with a dual task. To test this, we designed an experiment to investigate the mental workload associated with different postural and mental tasks and verify whether the provision of a haptic support changes the mental workload. If our hypothesis held true, we would expect (a) different postural conditions yield different frontal workloads, (b) that frontal workload reflects the difficulty of the task proposed and (c) that the provision of touch modulates the overall frontal workload. Determining the directionality of this modulation, whether in terms of decreasing frontal lobe activation as a sign of reduced cognitive load or increasing activation signalling more resources available is complex to define and will be further discussed in the next paragraphs. The experiment was conducted on four different populations, namely young adults with no disabilities, young adults with Down Syndrome, older people with no disabilities and older people with the diagnosis of Dementia. We used functional near-infrared spectroscopy (fNIRS) to monitor blood flow (and hence neural activation) specifically in the right dorsolateral pre-frontal areas.

Functional Near-Infrared Spectroscopy (fNIRS) has become an increasingly vital tool in neuroscience research, particularly in the study of brain function and its relationship to various cognitive and motor activities. As a non-invasive imaging technique, fNIRS offers a unique advantage by enabling the monitoring of brain activity through the detection of changes in blood oxygenation levels, a process that is closely linked to neuronal activity. The technique is based on the principles of near-infrared light absorption by biological tissues, specifically haemoglobin, the molecule responsible for transporting oxygen in the blood. Near-infrared light in the wavelength range of approximately 650 to 950 nanometres, has the unique ability to penetrate biological tissues, including the human skull, to a depth of several centimetres. This penetration allows the light to reach the cerebral cortex, where it is differentially absorbed by oxygenated and deoxygenated haemoglobin (Ferrari and Quaresima, 2012). The difference in absorption properties between these two forms of haemoglobin forms the basis of fNIRS measurements. When neurons are active, they consume oxygen, leading to a localized increase in deoxygenated haemoglobin. This change triggers a compensatory response where oxygenated blood is delivered to the area, resulting in a transient increase in oxygenated haemoglobin and a corresponding decrease in deoxygenated haemoglobin. The fNIRS system capitalizes on this physiological process by using sensors placed on the scalp to emit near-infrared light into the brain and detect the light that is either absorbed or scattered back to the sensors. By analysing the patterns of light absorption, researchers can infer changes in blood oxygenation levels, and thus neuronal activity, in real-time (Boas et al., 2014).

Over the past decade, fNIRS has gained considerable traction as a powerful and versatile tool for exploring the intricate relationship between posture and cognition. The versatility of fNIRS lies in its portability, ease of use, and ability to provide continuous, real-time data on brain function in naturalistic settings, which makes it particularly well-suited for studying complex cognitive tasks that involve motor components, such as maintaining posture while performing cognitive tasks. For example, recent studies have utilized fNIRS to investigate how postural control influences cognitive processing, revealing important insights into the neural mechanisms that underlie the interaction between these two domains (Scholkmann et al., 2014).

One of the significant areas of application for fNIRS has been the investigation of cognitive load during dual-task paradigms, where an individual is required to perform a cognitive task while simultaneously maintaining postural stability. This line of research is crucial for understanding how the brain allocates resources when faced with competing demands, a situation that is common in everyday life, especially in populations with compromised cognitive or motor abilities, such as the elderly or individuals with neurological disorders. Almulla et al. (2020) conducted a study using fNIRS to assess cognitive load during a cognitive-motor dual task, finding that the prefrontal cortex, a region of the brain associated with higher-order cognitive functions, showed increased activation as the complexity of the task increased. Similarly, Menant et al. (2020) used fNIRS to examine the effects of cognitive load on postural control in older adults, demonstrating that higher cognitive demands were associated with greater activation in the prefrontal cortex and poorer postural stability, highlighting the intricate balance between cognitive and motor processes. The cognitive load paradigm does not always assume that increased load corresponds to increased fatigue. For example, in populations with developmental disabilities or dementia, fNIRS studies have shown reduced activation in the prefrontal and frontal lobes compared to controls without disabilities. This reduction in activation is interpreted as a diminished capacity to allocate mental resources toward specific tasks (Monden et al., 2015; Xu et al., 2020; Husain et al., 2023; Mei et al., 2023; Liampas et al., 2024).

The use of fNIRS in these studies underscores its efficacy in capturing the dynamic interplay between cognitive and motor functions, particularly in dual-task scenarios that mimic real-world challenges. Its ability to provide insights into the neural correlates of cognitive load and motor control simultaneously offers significant implications for the development of interventions aimed at improving cognitive and motor performance, particularly in vulnerable populations. Moreover, the growing body of literature on the use of fNIRS to explore posture-cognition relationships is contributing to a deeper understanding of how the brain integrates sensory, cognitive, and motor information to produce coordinated behaviour, paving the way for new approaches to enhance human performance across a range of settings, from clinical to athletic contexts (Herold et al., 2018).

In summary, Functional Near-Infrared Spectroscopy has emerged as a promising and efficient tool in the investigation of the relationship between posture and cognition, with a particular emphasis on its application in cognitive-motor dual tasks. Its non-invasive nature, coupled with its ability to provide real-time monitoring of brain function, makes it an invaluable resource for researchers seeking to unravel the complex interactions between cognitive processes and motor behaviour. The insights gained from fNIRS studies have the potential to inform the development of targeted interventions aimed at improving cognitive and motor outcomes, particularly in populations where these abilities are compromised. As research in this field continues to evolve, fNIRS is likely to play an increasingly important role in advancing our understanding of the neural mechanisms underlying posture-cognition interactions and their implications for human health and performance (Scholkmann et al., 2014; Pinti et al., 2019).

5.2 Material and methods

5.2.1 Participants

72 participants were recruited for this study. 30 participants were young adults with no referred disability and of age comprised between 18 and 35 years [13 male, 17 female, 27.73 yo, 3.43 sd], 21 participants were adults with no referred disability of age comprised between 58 and 75 years [17 male, 4 female, 66.85 yo, 5.16 sd], 14 participants were young adults with Down Syndrome of age comprised between 18 and 35 years [10 male, 4 female, 24.14 yo, 5.90 sd], 7 participants were adults who had received a diagnosis of Dementia in the last 5 years, of age comprised between 57 and 75 years [6 male, 1 female, 68 yo, 5.16 sd]. In **table 5.1** we reported for each participant with dementia

the precise diagnosis. Participants with Dementia were recruited with the help of "Associazione Novilunio APS", an Italian social promotion association committed to promoting the dignity, social inclusion, and rights of people with dementia and their families. Each participant was accompanied by a related person (friend, partner, parent) who was deputed to the provision of a physical support during half of the tasks.

Participant	Diagnosis	Age
PW1	FrontoTemporal Dementia	70
PW2	Alzehimer	64
PW3	Cadasil	57
PW4	Alzheimer	73
PW5	Alzheimer	65
PW6	Alzehimer	72
PW7	Alzheimer	75

Table 5.1. Description of participants with Dementia.

5.2.2 Study design.

The study was designed to measure participants' blood flow variation during the accomplishment of a motor-cognitive dual task while the levels of difficulty of the motor and cognitive task and the provision of an external, haptic, physical support were modulated.

For each task two variants were generated. Thus, eight experimental conditions were created by systematically manipulating the combinations of factors representing motor and cognitive tasks and the provision of physical support.

Below the tasks are presented.

*Cognitive task: p*articipants were asked to perform a Schulte's table at two different levels of difficulties. A Schulte's table typically appears as a square grid, with dimensions ranging from 3x3 to 9x9 or even larger. Each square within the grid usually contains a single digit. Digits range between 1 and n, in the basic version of Schulte's table, with n representing the total number of squares in the grid. Some versions allow for the modification of the offset, and for adopting non sequential numbers. The numbers are arranged in a randomly in the grid. The goal of the task is to locate and point at the numbers in a precise sequential order.

A Schulte's table is a cognitive task that involves visuospatial working memory (Khramova et al., 2021); since its accomplishment requires the coordination of multiple sequential pointing gestures it also sets the ground to start exploring the interference between cognitive and sensorimotor tasks and the integration of touch in this dual task set-up.

A customized version of the Schulte's table was designed for this study. In this version of the Schulte's table, we could manipulate the size of the grid and the task's goal, therefore the indication of the correct sequence of number that could solve the grid. Four different sequence orders were implemented:

- Ascending order: from the lowest to the highest number (for example: 1, 2, 3, 4, 5, 6, …)
- Descending order: from the highest to the lowest number (for example: 25, 24, 23, 22, 21, …)
- Multivariate order: alternate the ascending count with a descending count (for example, given a 5x5 grid, with digit from 1 to 25, the correct sequence is: 1, 25, 2, 24, 3, 23, 4, 22, 5, 21, …)
- Multivariate2 order: alternate the descending count with an ascending count (for example given a 5x5 grid, with digit from 1 to 25, the correct sequence is: 25, 1, 24, 2, 23, 3, 22, 4, 21, 5, …)

The Schulte's table was presented on an iPad mini. Once the correct digit was tapped, the square in the grid that hosted the number turns red for 500 milliseconds, signalling the users they are following the correct sequence. If the users tapped at an incorrect digit nothing would be signalled in the grid. The customized version of the Schulte's table registered the inter keystroke interval, the accuracy of the task (number of wrong digits tapped) and the complex duration of the task. Once completed the task, these results were automatically downloaded on the iPad.

In the context of a Schulte's table, the difficulty of the task is determined by the number of digits displayed and by the sequence the users have to follow to correctly complete the task. A higher grid size expands the range on which the user has to perform the visual search. A non-conventional sequence of number would require the user to keep track of the correct sequence while orientating on the grid to find the target digit.

For our study, we chose a 5x5 grid's size, where 1 to 25 digits were displaced. Two levels of difficulty were selected. In the easier condition, we asked participant to find and tap numbers in a descending order. In the harder condition, participants were asked to find and tap numbers in the multivariate2 order, therefore parallelly descending from 25 and ascending from 1. It was possible to keep these tasks constant with the population groups with no disability.

In the context of participants with Down Syndrome and in some cases with Dementia, we had to adjust the task difficulty to participant competence. Therefore, in the easier task condition, participants were asked to point at numbers in ascending order, and in the harder task condition to point at numbers in descending order. In the harder task, for some participants, the backwards count was possible just from 16 to 1. In these circumstances the grid was reduced to a 4x4 size.

*Motor task: p*articipants were asked to maintain either a sitting or standing posture.

In the sitting condition, participants were asked to maintain an upright trunk's posture, without resting their back on the chairs' backseat and keeping their feet on the ground. In the standing condition, participants were asked to maintain a close feet stance. A cross was designed on the ground as a positional reference point. In both tasks, participants were instructed to hold the tablet with their not-dominant arm and to rise the tablet at a sight distance that did not interfere with the maintenance of the upright trunk's posture. Participants were invited to maintain the position assigned during the baseline and throughout the execution of the cognitive task.

The postural tasks were designed so that, while maintaining their safety, participants would experience some balance perturbation. The close feet stance reduces the base of support, challenging proprioception and requiring subtle adjustments in weight distribution to maintain stability. Similarly, adopting an upright sitting posture with no backseat rest engages core muscles and prompts participants to rely on their own postural control to maintain balance, fostering a more dynamic and interactive experience within the task.

*Physical support provision: d*uring the accomplishment of part of the cognitive-motor dual tasks, participants were provided with a light non-load bearing touch-based support. The touch was provided by the participant's partner at the level of the back. The partner was instructed to provide a gentle touch that could provide a positional reference without interfering with the participant balance, by applying forces to counteract body sway oscillations.

5.2.3 Task sequence

The combination of the different tasks and their respective binary levels of difficulty determined eight different experimental conditions:

Condition 1: NO TOUCH-SITTING-EASY COGNITIVE (N1X)

Condition 2: NO TOUCH-SITTING-HARD COGNITIVE (N1Y)

Condition 3: NO TOUCH-STANDING-EASY COGNITIVE (N2X)

Condition 4: NO TOUCH-STANDING-HARD COGNITIVE (N2Y)

Condition 5: TOUCH-SITTING-EASY COGNITIVE (T1X)

Condition 6: TOUCH-SITTING-HARD COGNITIVE (T1Y)

Condition 7: TOUCH-STANDING-EASY COGNITIVE (T2X)

Condition 8: TOUCH-STANDING-HARD COGNITIVE (T2Y)

Participants were asked to complete two consecutive attempts for each condition, for a total of 16 Schulte's table each. Within each group, the order of presentation of the tasks was randomized.

5.2.4 Data collection

Pre-test

Participants were asked to engage with some pre-test before starting the NIRS measurement. The pre-tests consisted of a balance and gait assessment using the "Tinetti scale" (Curcio et al., 2016), an auditory working memory test, using the "Digit memory test" (Turner and Ridsdale, 2004) and a processing speed test using the Digit Symbol Substitution Test (DSST) (Jaeger, 2018).

Familiarization with the task

Participants were asked to try the two different cognitive task to get some familiarity both with the tablet and the task. This phase was the occasion to investigate the level of participants competencies and in case adjust the level of difficulty of task.

NIRS cap

Each participant was asked to wear NIRS Headcap. The Artinis' BRITE-2 system was used for this data collection. The headcap hosted 36 optodes, 20 transmitters and 16 receivers that generated a network of 54 channels, displaced on the fronto-temporal areas of both the right and left hemispheres.

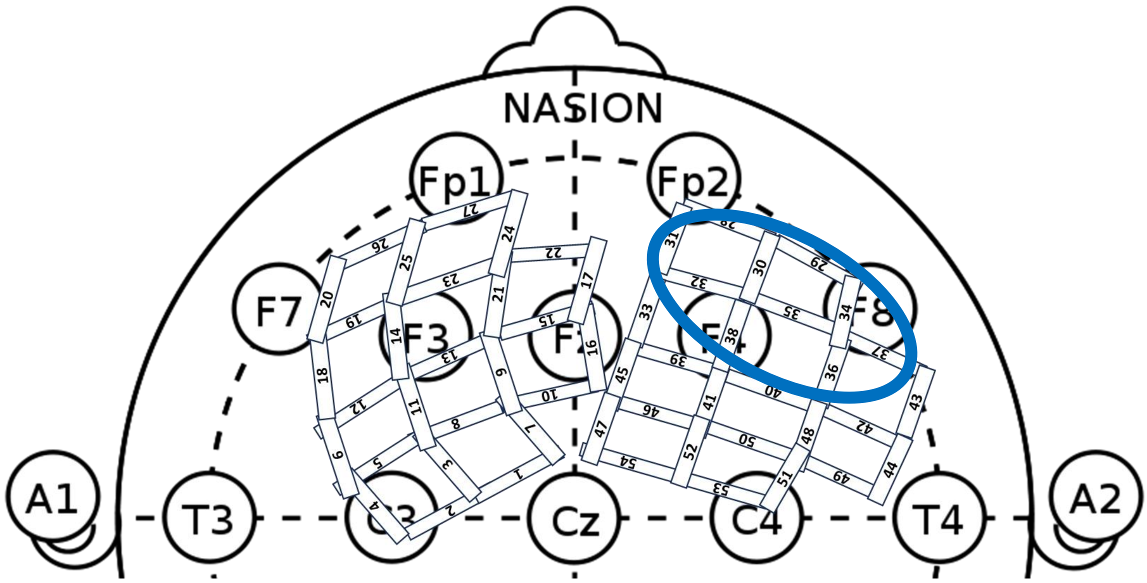


Figure 5.1. Displacement of fNIRS Optodes. This figure illustrates the arrangement of the optodes used during data collection. The channels' area circled in blue correspond to the right dorsolateral prefrontal cortex, which were specifically analysed in the study

After being informed of the basic functioning of the equipment, users were asked to wear the cap and position it just above the eyebrows' line. Then, the researcher manually fixed the optode-scalp coupling by removing with a thin stick any hair in between the optodes and the scalp.

Baseline and task execution

Once the optode-scalp coupling was fine-tuned the experiment could start. The researcher initiated the Oxysoft registration. Participant were informed of the condition of the coming up task. In the case of a sitting task, they were asked to sit comfortably on the chair, in the case of standing task to stand comfortably. Then, once the researcher called for the baseline, participants were instructed to adapt their posture to the one required by the task: sitting with an upright trunk or standing in a close feet stance. If the condition required so, the light touch was applied during the baseline. During these 10-20 seconds baseline participants were asked to empty their mind and to visually look at a 5x5 grid with Xs replacing the digits within the grid's squares.

Finally, once the researchers called for the task to start, participants were asked to press start on their tablet and perform the tasks as fast as they could without neglecting their accuracy. In a separate sheet, the researchers annotated the timestamp of the task start in relation to the NIRS registration timer. Once the participants finished the task they were granted of some minutes of break, before continuing with the following task. **In figure 5.2** the data collection design is reported.

Figure 5.2. Data collection block design. The block consists of four phases: (1) Rest (Pre-task) to establish a baseline, (2) Baselining to calibrate fNIRS signals, (3) Task, where participants perform sensorimotor and cognitive tasks, and (4) Rest (Post-task) to allow signals to return to baseline.

5.3 Data pre-processing

The data collected through the Oxysoft software were exported in the ".oxy3" format and extracted in MATLAB using the "oxysoft2matlab.m" function. The preprocessing pipeline is summarized in **figure 5.3** and followed the guidelines proposed in Pinti (2019) and commented by Bizzego (2020).

The prolonged duration of the task presented to our participants combined with the postural demands of the task, specifically designed to perturbate the sitting and standing balance of the trunk, the acquisition of NIRS data was exposed to the risk of incorporating motion artifacts. In the context of NIRS, motion artefacts refer to distortions in the measured signal due to head movements that may produce a slip in the scalp-optode coupling. To handle the spikes in the signal due to head-motion we applied a Wavelet filtering (IQR = 1) to the fNIRS signal of all the channels. Wavelet filtering is one of the most used solutions that allows researchers to deal with motion artefacts without losing a significant amount of data (Scholkmann et al., 2010; Brigadoi et al., 2014; Huang et al., 2019; Pinti et al., 2019; Al-Omairi et al., 2023). As a second step, a bandpass filter (lpf = 0, hpf = 0.5) was applied to the data to remove any physiological noise in the signal (heartbeat, breathing, Mayers' wave, blood pressure…). Finally, the NIRS data were transformed into oxygen concentrations, with the HOMER 3 in-built function that exploits the Beer-Lambert equation.

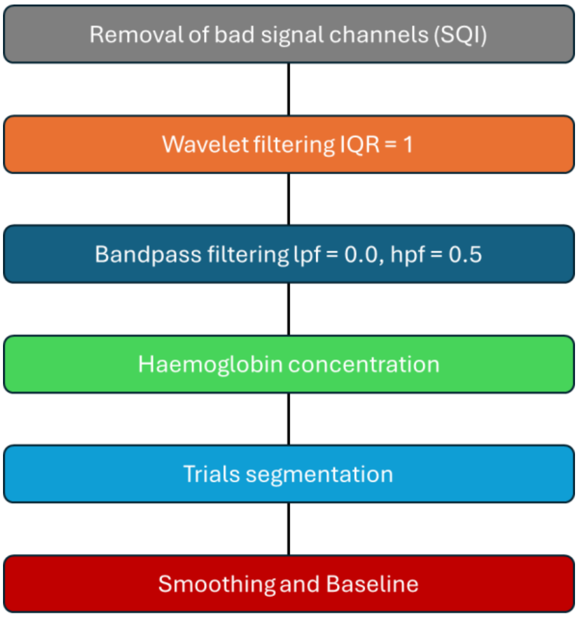


Figure 5.3. fNIRS signals' preprocessing pipeline. This figure outlines the key steps involved in preprocessing the fNIRS signals prior to analysis. The pipeline begins with raw signal acquisition from the fNIRS device, followed by signal quality checks to remove artifacts and noise. A wavelet filtering is applied to remove motion artifacts, then the signal is band-pass filtered. Optical signals are transformed into Haemoglobin concentration using the Beer-Lamber function. The processed signals are then segmented into task-specific time windows. Baseline correction is then applied to account for signal drift.

Once the data were pre-processed, they were chunked into trials. Each trial included the full duration of task performance plus the 10 seconds of baseline that preceded the execution of the task. Finally, the data were smoothed, and the baseline removed. The Oxygenated Haemoglobin (HBO) value and the Deoxygenated Haemoglobin (HBR) value at the end of the baseline period were respectively removed from the whole HBO or HBR signals. The baseline period required the user to execute a postural task, with or without physical support. During this time, the experimental task was performed without the addition of the cognitive component. Considering the request for the user to empty their mind to be a particularly odd and complex one, it seemed more conservative to zeroing the HBO and HBR concentrations at the beginning of the cognitive task. From that point, we compared the effects of the different experimental conditions on blood flow.

In parallel to the HOMER 3 preprocessing pipeline, we applied to the raw optical and concentration data, chunked into trials, the signal quality index (SQI) function (Sappia et al., 2020), designed by Oxysoft for MATLAB. This function allowed us to calculate the signal quality in terms of scalp-optode coupling. The analysis returns for each channels a score between 1 and 5, with the scores of 1 and 2 indicating bad channel quality, a score of 3 indicating medium channel quality and the scores of 4 and 5 indicating good signal quality. Every channel, for each single trial that had a score equal or lower than 2 was then excluded from the analysis, then from the output of the preprocessing stream (Sappia et al., 2020).

5.4 Results

5.4.1 Pre-test results

Before starting the data collection, each participant was asked to perform a pre-test: a postural stability test (Tinetti Performance Oriented Mobility Assessment) and a digit symbol substitution task (DSST), that evaluate participants' processing speed. The performance analysis at the pre-test shows that, consistently with what should be expected, age and disability lead to a decrease in both postural stability and processing speed. In particular, as shown by figure 5.4a young participants with no disability show on average higher raw score at the DSST, followed by participants belonging to the elderly population group, and participants with Down Syndrome. Participants with a diagnosis of Dementia had the lowest DSST average raw score. With respect to postural stability, figure 5.4b, the pre-test analysis also reports postural stability performances decreasing with age and disability. The Tinetti scale's scores are categorized in three tiers: high fall risk (<19 RS), medium fall risk (19 - 24), low fall risk (25-28). Of the participant we assessed, only the population with Down Syndrome scored on average below at the medium fall risk, with half of the participants having Tinetti scores between 22 and 24.

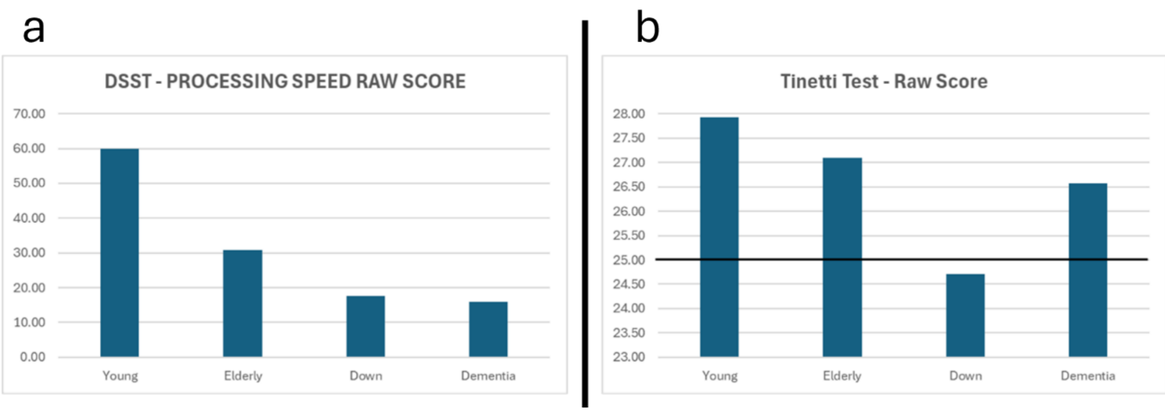


Figure 5.4. Pre-testing results. In figure a, the average raw score for each group of participants at the digit symbol substitution test (DSST) is reported. Performance scores reduce with age and disability. In figure b, the average raw score for each group of participants at the Tinetti test is reported. Postural performances reduce with age and disability.

5.4.2 Performance results

In this section we report the analysis of participants performance, intended as the time required to accomplish the Schulte's table.

A mixed 2 (Posture: easy, hard) x 2 (Load: easy, hard) x 2 (Touch: y/n) x 2 (Age: Y/O) x 2 (Disability: y/n) ANOVA was conducted with Posture, Load and Touch as within subjects' factors and Age and Disability as between subjects' factors. The Mixed Anova results are reported in Table 5.2.

The results report a main effect of LOAD on the task performance ($F= 103.119$, $p <0.001$; high load tasks took longer to be completed with respect to low load tasks). The analysis reports a two ways interaction of AGE and LOAD ($F = 8.651$, $p = 0.004$), a two ways interaction of LOAD and DISABILITY ($F = 25.624$, $p < 0.001$) and a two ways interaction between TOUCH and LOAD ($F = 7.258$, $p = 0.009$). A three ways interaction (TOUCH x LOAD x DISABILITY, $F = 6.672$, $p = 0.012$) and a four ways interaction (TOUCH x POSTURE x AGE x DISABILITY, $F = 5.628$, $p = 0.02$) are also reported in the analysis. Although significant interactions involving posture and touch were found in relation to cognitive performance, the simple main effects analysis does not reveal clear, significant effects for these variables. Instead, the observed differences are primarily driven by load age or disability.

Looking more closely at the single group analysis, regardless of the load, the performance duration of people with Down Syndrome is significantly lower ($p <0.01$) when a haptic touch is provided during a standing task. The same difference is also reported in the young population with Down Syndrome when the load of the task is high in the standing postural condition. Touch also plays a significant role in the elderly population with Dementia, during low load task in sitting postural condition. Here, the provision of haptic support has an inversed effect and leads to a significant decrease ($p <0.01$) of participants' performance duration, determining a longer time for the participants to accomplish the task, (see figure 5.5).

Performance in each condition for each group is reported separately in figure 5.6.

Speed of performance decreased with age and disability. Across the data collection and consistently with what emerged from the pre-testing analysis, young participants were faster in accomplishing the Schulte's table across different conditions, followed by Elderly participants and participants with Dementia. Down Syndrome average performance speed could not be compared to that of the other participants as the task the participants were asked to accomplish was a reduced and simpler version with respect to that presented to the other participants. What clearly emerged from the picture is that load effect is wider in the population with no disability where significant speed difference between the High and Low Load tasks are reported in all the different conditions. In the population with disability, load differences are just reported in the no-touch condition during the sitting and standing task in the participants with Dementia. No Load difference is reported in the population with Down Syndrome. As previously seen, the touch effect in performance is reported in the population with Dementia, in the accomplishment of Low cognitive load tasks in the sitting condition. Here the provision of touch leads to a reduced performance speed. In the population with DS, touch significantly increased performance speed during the accomplishment of high load cognitive tasks in the standing condition.

Tests of Within-Subjects Contrasts

Measure: MEASURE_1

Source	TOUCH	POSTURE	LOAD	Type III Sum of Squares	df	Mean Square	F	Sig.	Squared
TOUCH	Linear			15920.857	1	15920.857	0.109	0.743	0.002
TOUCH * AGE	Linear			338853.229	1	338853.229	2.314	0.133	0.033
TOUCH * DISABILITY	Linear			180769.573	1	180769.573	1.235	0.270	0.018
TOUCH * AGE * DISABILITY	Linear			116378.397	1	116378.397	0.795	0.376	0.012
Error(TOUCH)	Linear			9809553.894	67	146411.252			
POSTURE		Linear		34769.079	1	34769.079	0.118	0.732	0.002
POSTURE * AGE		Linear		265615.986	1	265615.986	0.905	0.345	0.013
POSTURE * DISABILITY		Linear		428.331	1	428.331	0.001	0.970	0.000
POSTURE * AGE * DISABILITY		Linear		40373.171	1	40373.171	0.137	0.712	0.002
Error(POSTURE)		Linear		19674308.350	67	293646.393			
LOAD			Linear	25546148.254	1	25546148.254	103.119	**0.000**	0.606
LOAD * AGE			Linear	2143236.912	1	2143236.912	8.651	**0.004**	0.114
LOAD * DISABILITY			Linear	6348034.295	1	6348034.295	25.624	**0.000**	0.277
LOAD * AGE * DISABILITY			Linear	46884.696	1	46884.696	0.189	0.665	0.003
Error(LOAD)			Linear	16598247.767	67	247735.041			
TOUCH * POSTURE	Linear	Linear		662.098	1	662.098	0.004	0.947	0.000
TOUCH * POSTURE * AGE	Linear	Linear		430473.310	1	430473.310	2.891	0.094	0.041
TOUCH * POSTURE * DISABILITY	Linear	Linear		161673.429	1	161673.429	1.086	0.301	0.016
TOUCH * POSTURE * AGE * DISABILITY	Linear	Linear		846230.563	1	846230.563	5.682	**0.020**	0.078
Error(TOUCH*POSTURE)	Linear	Linear		9977937.928	67	148924.447			
TOUCH * LOAD	Linear		Linear	724804.315	1	724804.315	7.258	**0.009**	0.098
TOUCH * LOAD * AGE	Linear		Linear	19409.419	1	19409.419	0.194	0.661	0.003
TOUCH * LOAD * DISABILITY	Linear		Linear	666286.474	1	666286.474	6.672	**0.012**	0.091
TOUCH * LOAD * AGE * DISABILITY	Linear		Linear	3789.102	1	3789.102	0.038	0.846	0.001
Error(TOUCH*LOAD)	Linear		Linear	6690367.507	67	99856.231			
POSTURE * LOAD		Linear	Linear	124083.880	1	124083.880	0.865	0.356	0.013
POSTURE * LOAD * AGE		Linear	Linear	14122.830	1	14122.830	0.098	0.755	0.001
POSTURE * LOAD * DISABILITY		Linear	Linear	589.018	1	589.018	0.004	0.949	0.000
POSTURE * LOAD * AGE * DISABILITY		Linear	Linear	59472.758	1	59472.758	0.414	0.522	0.006
Error(POSTURE*LOAD)		Linear	Linear	9615885.877	67	143520.685			
TOUCH * POSTURE * LOAD	Linear	Linear	Linear	126263.069	1	126263.069	0.780	0.380	0.012
TOUCH * POSTURE * LOAD * AGE	Linear	Linear	Linear	25063.615	1	25063.615	0.155	0.695	0.002
TOUCH * POSTURE * LOAD * DISABILITY	Linear	Linear	Linear	642224.111	1	642224.111	3.965	0.051	0.056
TOUCH * POSTURE * LOAD * AGE * DISABILITY	Linear	Linear	Linear	111397.169	1	111397.169	0.688	0.410	0.010
Error(TOUCH*POSTURE*LOAD)	Linear	Linear	Linear	10851710.316	67	161965.826			

Table 5.2. Task duration Mixed ANOVA: mixed 2 (Posture: easy, hard) x 2 (Load: easy, hard) x 2 (Touch: y/n) x 2 (Age: Y/O) x 2 (Disability: y/n) ANOVA was conducted with Posture, Load and Touch as within subjects' factors and Age and Disability as between subjects' factors. Task duration served as the dependent variable. This analysis examined how these factors interact to influence task completion time.

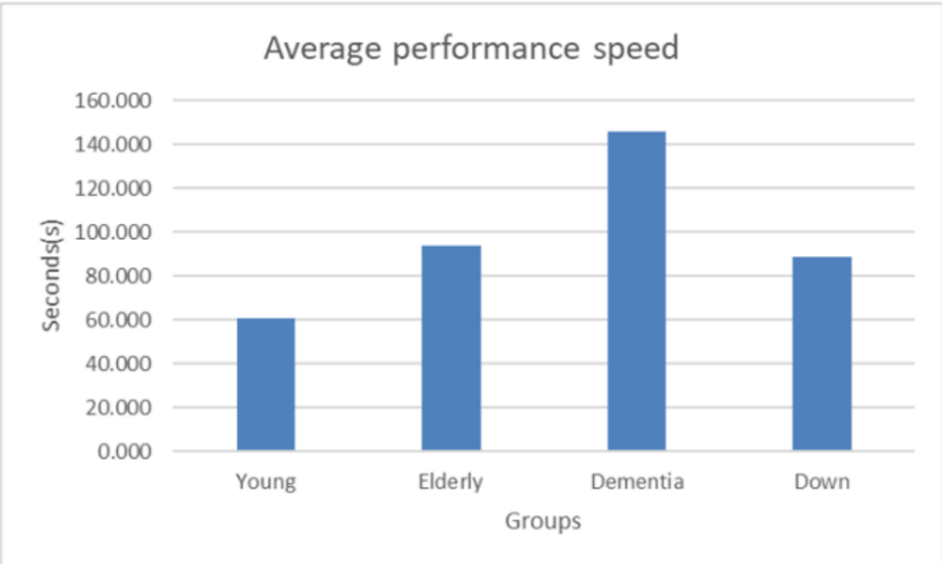


Figure 5.5. Task duration analysis. Figure 5.5 reports for each group the participants' average time required to accomplish the cognitive task (Schulte's table). Regardless of the participants with Down Syndrome, which had a simplified version of the task, the time required to accomplish the task increases with age and disability.

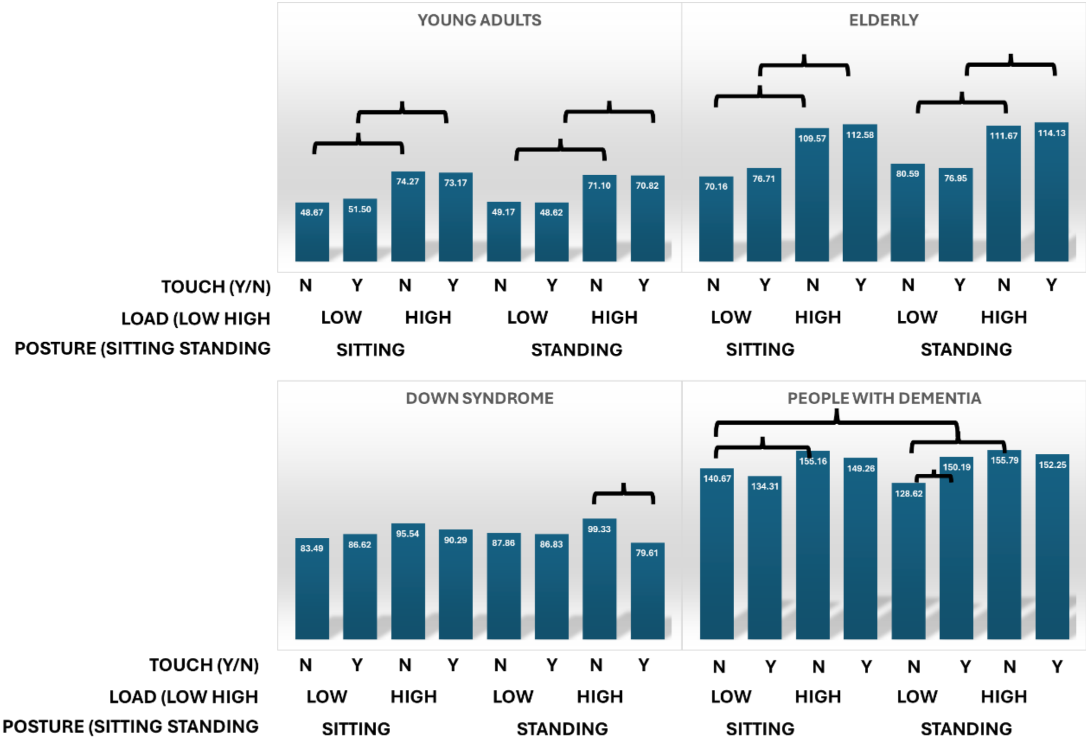


Figure 5.6. Averaged time required to accomplish the task. The figure reports the average task duration for each group in each experimental condition. In the population only load differences are reported. In the population with Down Syndrome, we report significant differences just between touch and no touch condition in the standing-hard cognitive task. In the population with dementia loads differences are reported only when no touch is provided to the participant.

5.4.3 fNIRS results

In this section, we report the results of the analysis of fNIRS signal. Here, we have considered Haemoglobin Oxygenation (HBO) levels in the right dorsolateral prefrontal cortex (RDLPFC), see figure 5.1. This area plays a crucial role in executive function, and adapting strategies to meet the demands of the task and particularly in visuospatial working memory tasks (Giglia et al., 2014). Dorsolateral prefrontal cortex was also shown to be strictly connected to the executive control of postural tasks like standing (Mirelman et al., 2014). With a reference to the 10-20 international notation system, RDLPFC is comprised between FP2, F4 and F8. The optodes set-up of our fNIRS cap covered the RDLPFC are with 13 channels. Here we provide an analysis of the average HBO levels during the accomplishment of the task comparing the 13 channels together.

The HBO levels in the RDLPFC were assessed through a structured process. Initially, the HBO levels from the two tasks undertaken by each participant in every experimental condition were averaged. Next, this averaged signal was baseline-corrected by subtracting the average HBO level during the 10-second baseline period. Subsequently, the HBO levels from all channels were aggregated, and from this combined signal, the average HBO levels during the initial 20 seconds of the task were computed.

For the analysis we considered only those users with at least 6 good quality channels in the RDLPFC; also, we considered only those channels with a good quality signal in all the touch-load combinations. For example, if a user had 13 good channels in six conditions (e.g. NO TOUCH-SITTING-LOW LOAD, NO TOUCH-SITTING-HIGH LOAD, TOUCH-SITTING-LOW LOAD, NO TOUCH-STANDING-LOW LOAD, NO TOUCH-STANDING-HIGH LOAD, TOUCH-STANDING-LOW LOAD) but only 6 good quality channels in the NO TOUCH-SITTING-HIGH LOAD and in the TOUCH-STANDING-HIGH LOAD conditions, we performed the analysis just of the same 6 channels for all the eight experimental conditions. This operation enabled us to consider in the analysis a fair number of channels (at least 50% of the channels) and to provide a homogenous comparison within the same subjects while not affecting too much the sample size. As a consequence, the analysis was conducted on the HBO levels of 55 participants divided as follows:

- Young adults with no disability = 23
- Elderly with no disability = 20
- Young adults with Down Syndrome = 6
- Elderly with Dementia = 6

A mixed 2 (Posture: easy, hard) x 2 (Load: easy, hard) x 2 (Touch: y/n) x 2 (Age: Y/O) x 2 (Disability: y/n) ANOVA was conducted with Posture, Load and Touch as within subjects' factors and Age and Disability as between subjects' factors.

The Mixed Anova results are displayed in Table 5.3.

The results report a significant main effect of Posture on HBO concentration levels ($F = 23.356$, $p < 0.001$; the sitting task is characterized by higher HBO concentration levels with respect to the standing task).

Two ways significant interactions are reported between touch and posture ($F(1,51) = 13.615$, $p = 0.001$) and marginally between touch and load ($F(1,51) = 3.069$, $p = 0.086$).

A significant three-ways interaction is reported between Touch Posture and Load ($F(1,51) = 5.035$, $p = 0.029$).

A significant four ways interaction is reported between touch, posture, load and age ($F(1,51) = 4.271$, $p = 0.044$).

Finally, the five-ways interaction (posture x touch x load x age x disability) is reported as significant ($F(1,51) = 4.366$, $p = 0.042$).

In summary, the analysis reveals complex interdependencies between touch, posture, load, age, and disability in their effects on HBO concentration levels. The significant interactions—particularly between touch and posture, and the three-way interaction of touch, posture, and load—highlight that the impact of these factors is not uniform but rather varies depending on specific combinations. Additionally, the significant four-way interaction between touch, posture, load, and age, as well as the five-way interaction involving all variables, underscores the nuanced and multi-faceted nature of these relationships.

To gain a deeper understanding of these interactions, the following paragraphs further explore the interaction effects, particularly focusing on how touch and posture interact across different levels of load, age, and disability. A closer evaluation of these effects, with a detailed examination of the interaction patterns, will provide clearer insights into the specific conditions under which each factor influences HBO concentration levels.

Figures 5.7-5.9 graphically display the simple main effect analysis, representing the interaction between touch and posture at different load in participants grouped by age or disability (figure 5.7), the interaction between touch and load at different postural conditions in participants grouped by age or disability (figure 5.8) and finally the average RDLPFC HBO concentration level for each single group (Young - Elderly - Down Syndrome - Dementia) in each single experimental condition (figure 5.9).

As it is possible to see from figure 1, postural conditions (sitting - standing) results with different HBO concentration levels, with the sitting task generally resulting in higher HBO levels compared to standing. If we consider all the group together (5.7a), the HBO concentration difference between the sitting (thick black line) and the standing postural task (dashed black line) is significantly different only when touch is provided. This is due to the reduction of HBO concentration levels due to touch in the standing condition and a parallel increasing of the HBO concentration levels due to touch in the sitting postural task.

If we further investigate this interaction differentiating the HBO concentration according to age and load, it is possible to notice that while the sitting postural task is characterized by greater HBO concentration levels with respect to the standing task, this difference is statistically significant only in the young population -young adults' group and Down syndrome group - (figure 5.7d and 5.7e) and only in the touch condition.

In this circumstance, it seems that touch is providing a divergent effect on HBO concentration levels according to the postural task: significantly increasing the HBO concentration level while sitting and significantly decreasing it while standing. If we observed the interaction between touch and posture under the perspective of load and disability (5.7f – 5.7i), it is possible to notice that in the population with no disability - young adults and Elderly - the HBO concentration levels is significantly higher in the sitting postural condition at both load and touch conditions (5.7f and 5.7g). So, whether touch is applied or not, or whether the concurrent cognitive task is easy or hard, sitting is denoted by significantly higher HBO concentration levels. However, in the population with disability, postural difference is reported just when touch is provided and in the standing postural condition (5.7i). The picture reported in 5.7i present evident similarities with the picture presented in 5.7e. In both pictures we observed a significant difference between sitting and standing in the high load - touch condition, delivered by a divergent effect of touch on HBO concentration levels (increasing in the sitting condition and decreasing in the standing condition). The common factor between the two groups - Young and With Disability - is represented by the participants with Down Syndrome. As we can see in figure 5.9, touch driven differences are statistically significant (although with a divergent direction) in both sitting and standing task during the accomplishment of high load cognitive tasks.

In figure 5.8, we further explore the simple main effect analysis of the interaction between touch and load at different postural condition in all participants together (5.8a – 5.8b) and in participants grouped by age (5.8c-5.8f) and by disability (5.8g – 5.8j).

As it is possible to notice from figure 5.8a and 5.8b, the provision of touch (dashed black line) determines higher HBO concentration levels during the sitting postural task and lower concentration levels during standing postural tasks. This difference is however significant just during High Load cognitive tasks. If we further into this interaction by grouping participant by age, it is possible to observe that while this trend is replicated either in the Elderly group and in the young group, statistically significant differences are reported only in the young group, again during High Load cognitive tasks 5.8e and 5.8f). Interestingly, in 5.8e, the provision of touch is determining significantly difference in HBO concentration levels between low load cognitive task and high load cognitive task when sitting. Contrarywise, in 5.8f, the absence of touch in the standing condition is determining significantly higher HBO concentration levels during the high load cognitive task. If we explore the interaction of touch and load at different postural condition by grouping participants by their level of disability - no disability and with disability - we observe a significant but divergent effect of touch in the population with disability (5.8i and 5.8j) in both postural condition and during high load cognitive tasks. Here again, touch increases the HBO concentration level while sitting and decreases it while standing. Interestingly, in the population with no disability, the provision of touch is significantly increasing the HBO concentration levels during standing - easy cognitive tasks. This result is also replicated in the single analysis of the young adults' group (figure 5.9).

The analysis at the single group level (five-way interaction) is reported in figure 5.9, where we have plotted the topographic of the average HBO concentration level in the right dorsolateral prefrontal cortex. As it is possible to notice from the picture, in the population with no disability - young and elderly - postural task determine most of the statistically significant differences acknowledged, with sitting having higher HBO concentration level than standing (a1 - a5, a2 - a6, a4 - a8, b1 - b5, b3 - b7, b4 - b8). If we refer to the population with disability - people with Dementia or Down Syndrome - significant differences driven by the sole postural task are acknowledged in the Down Syndrome population during high load task with the provision of touch (c4- c8). No significant load differences were reported in the fNIRS analysis at single group level, in contrast with what reported by the performance analysis where the cognitive task load was the most impacting factor.

As regarding the effect of touch, statistically significant differences (black brackets) are acknowledged in Down Syndrome group, however with a divergent directionality. In the sitting condition, during high load tasks, touch is increasing the HBO concentration level while in the standing task (c7 - c8) it works oppositely, with touch reducing the overall HBO concentration level.

Also, in the participants with Dementia we observe a trend of touch driven HBO concentration reduction in the standing high and low load condition. However, this differences, while visible is not statistically significant (d5-d6, d7-d8).

Finally in figure 5.10, we have plotted the average activation across all conditions for all the four group of participants. It is possible to notice, how HBO concentrations levels increase with age and with disability, with participants belonging to the young adults' group having lower HBO concentration level, followed by elderly participants, participants with Dementia and finally by participants with Down Syndrome who across conditions have the higher levels of HBO concentration in the RDLPFC.

Tests of Within-Subjects Contrasts

Measure: MEASURE_1

Source	TOUCH	POSTURE	LOAD	Type III Sum of Squares	df	Mean Square	F	Sig.	Squared
TOUCH	Linear			5.494E-11	1	5.494E-11	0.936	0.338	0.018
TOUCH * AGE	Linear			6.428E-11	1	6.428E-11	1.095	0.300	0.021
TOUCH * DISABILITY	Linear			8.261E-11	1	8.261E-11	1.407	0.241	0.027
TOUCH * AGE * DISABILITY	Linear			2.128E-12	1	2.128E-12	0.036	0.850	0.001
Error(TOUCH)	Linear			2.995E-09	51	5.872E-11			
POSTURE		Linear		1.616E-09	1	1.616E-09	23.356	**0.000**	0.314
POSTURE * AGE		Linear		4.562E-10	1	4.562E-10	6.595	**0.013**	0.115
POSTURE * DISABILITY		Linear		2.416E-11	1	2.416E-11	0.349	0.557	0.007
POSTURE * AGE * DISABILITY		Linear		4.273E-10	1	4.273E-10	6.177	**0.016**	0.108
Error(POSTURE)		Linear		3.528E-09	51	6.917E-11			
LOAD			Linear	1.898E-10	1	1.898E-10	2.377	0.129	0.045
LOAD * AGE			Linear	1.519E-10	1	1.519E-10	1.902	0.174	0.036
LOAD * DISABILITY			Linear	2.510E-10	1	2.510E-10	3.144	0.082	0.058
LOAD * AGE * DISABILITY			Linear	2.312E-10	1	2.312E-10	2.895	0.095	0.054
Error(LOAD)			Linear	4.072E-09	51	7.985E-11			
TOUCH * POSTURE	Linear	Linear		7.732E-10	1	7.732E-10	13.615	**0.001**	0.211
TOUCH * POSTURE * AGE	Linear	Linear		4.156E-10	1	4.156E-10	7.318	**0.009**	0.125
TOUCH * POSTURE * DISABILITY	Linear	Linear		6.842E-10	1	6.842E-10	12.048	**0.001**	0.191
TOUCH * POSTURE * AGE * DISABILITY	Linear	Linear		2.192E-10	1	2.192E-10	3.859	0.055	0.070
Error(TOUCH*POSTURE)	Linear	Linear		2.896E-09	51	5.679E-11			
TOUCH * LOAD	Linear		Linear	6.080E-12	1	6.080E-12	0.089	0.766	0.002
TOUCH * LOAD * AGE	Linear		Linear	1.079E-11	1	1.079E-11	0.159	0.692	0.003
TOUCH * LOAD * DISABILITY	Linear		Linear	2.914E-11	1	2.914E-11	0.428	0.516	0.008
TOUCH * LOAD * AGE * DISABILITY	Linear		Linear	1.613E-12	1	1.613E-12	0.024	0.878	0.000
Error(TOUCH*LOAD)	Linear		Linear	3.470E-09	51	6.804E-11			
POSTURE * LOAD		Linear	Linear	1.811E-10	1	1.811E-10	3.069	0.086	0.057
POSTURE * LOAD * AGE		Linear	Linear	3.001E-12	1	3.001E-12	0.051	0.822	0.001
POSTURE * LOAD * DISABILITY		Linear	Linear	9.163E-11	1	9.163E-11	1.553	0.218	0.030
POSTURE * LOAD * AGE * DISABILITY		Linear	Linear	1.347E-10	1	1.347E-10	2.282	0.137	0.043
Error(POSTURE*LOAD)		Linear	Linear	3.010E-09	51	5.901E-11			
TOUCH * POSTURE * LOAD	Linear	Linear	Linear	3.545E-10	1	3.545E-10	5.035	**0.029**	0.090
TOUCH * POSTURE * LOAD * AGE	Linear	Linear	Linear	3.007E-10	1	3.007E-10	4.271	**0.044**	0.077
TOUCH * POSTURE * LOAD * DISABILITY	Linear	Linear	Linear	1.362E-10	1	1.362E-10	1.934	0.170	0.037
TOUCH * POSTURE * LOAD * AGE * DISABILITY	Linear	Linear	Linear	3.074E-10	1	3.074E-10	4.366	**0.042**	0.079
Error(TOUCH*POSTURE*LOAD)	Linear	Linear	Linear	3.591E-09	51	7.041E-11			

Table 5.3. HBO concentration levels Mixed ANOVA: mixed 2 (Posture: easy, hard) x 2 (Load: easy, hard) x 2 (Touch: y/n) x 2 (Age: Y/O) x 2 (Disability: y/n) ANOVA was conducted with Posture, Load and Touch as within subjects' factors and Age and Disability as between subjects' factors. The average HBO concentration level in the right Dorsolateral Prefrontal cortex served as the dependent variable.

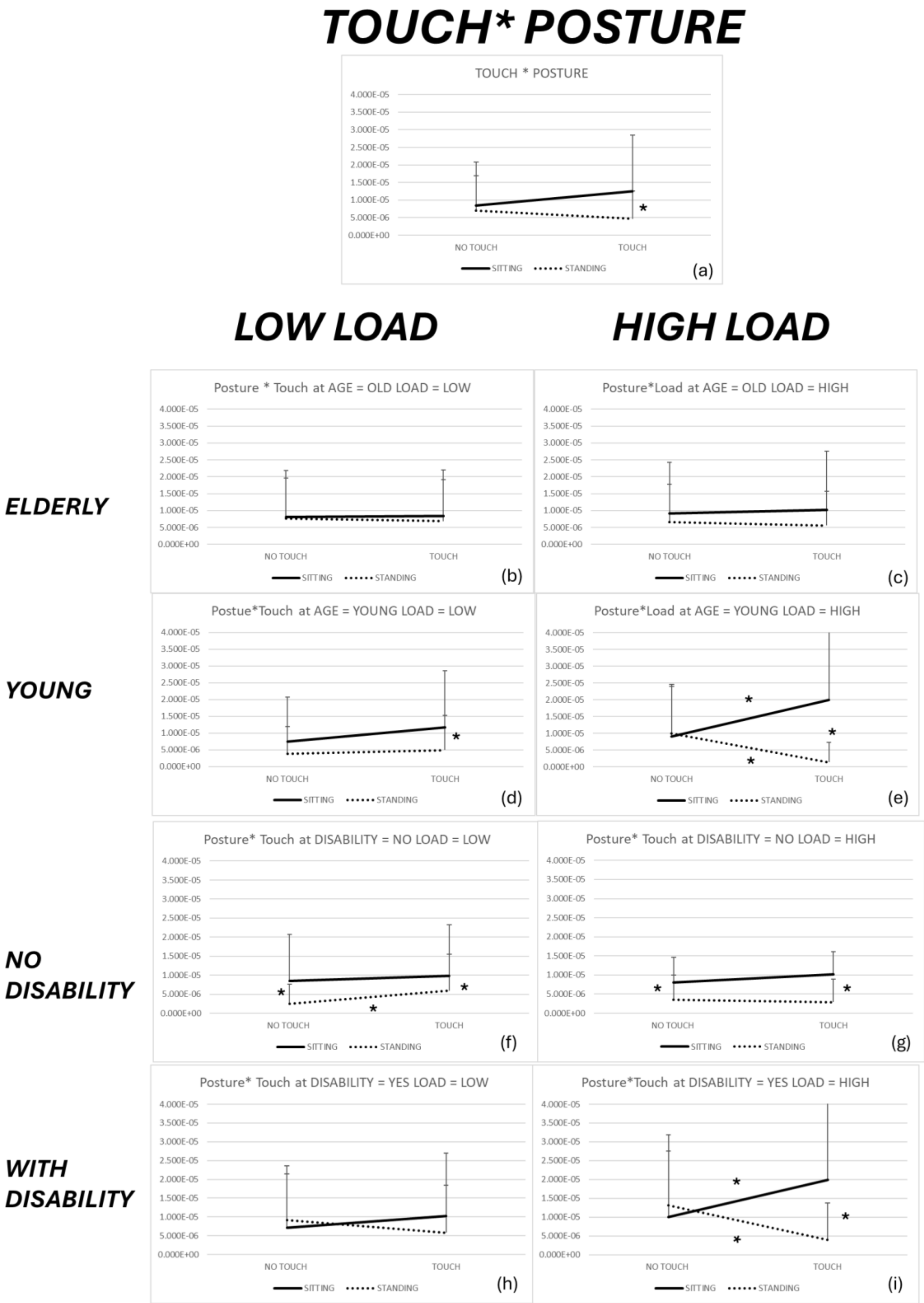


*Figure 5.7. Interaction of touch and posture under different load conditions. The graph illustrates the effects of touch (with and without) and posture (sitting (black line) vs. standing (dashed line)) on the dependent variable (e.g., HBO concentration levels) across the two load conditions: low load and high load. Significant effects are marked with an asterisk (*p < 0.05). Please refer to the main text for a full comment of the picture.*

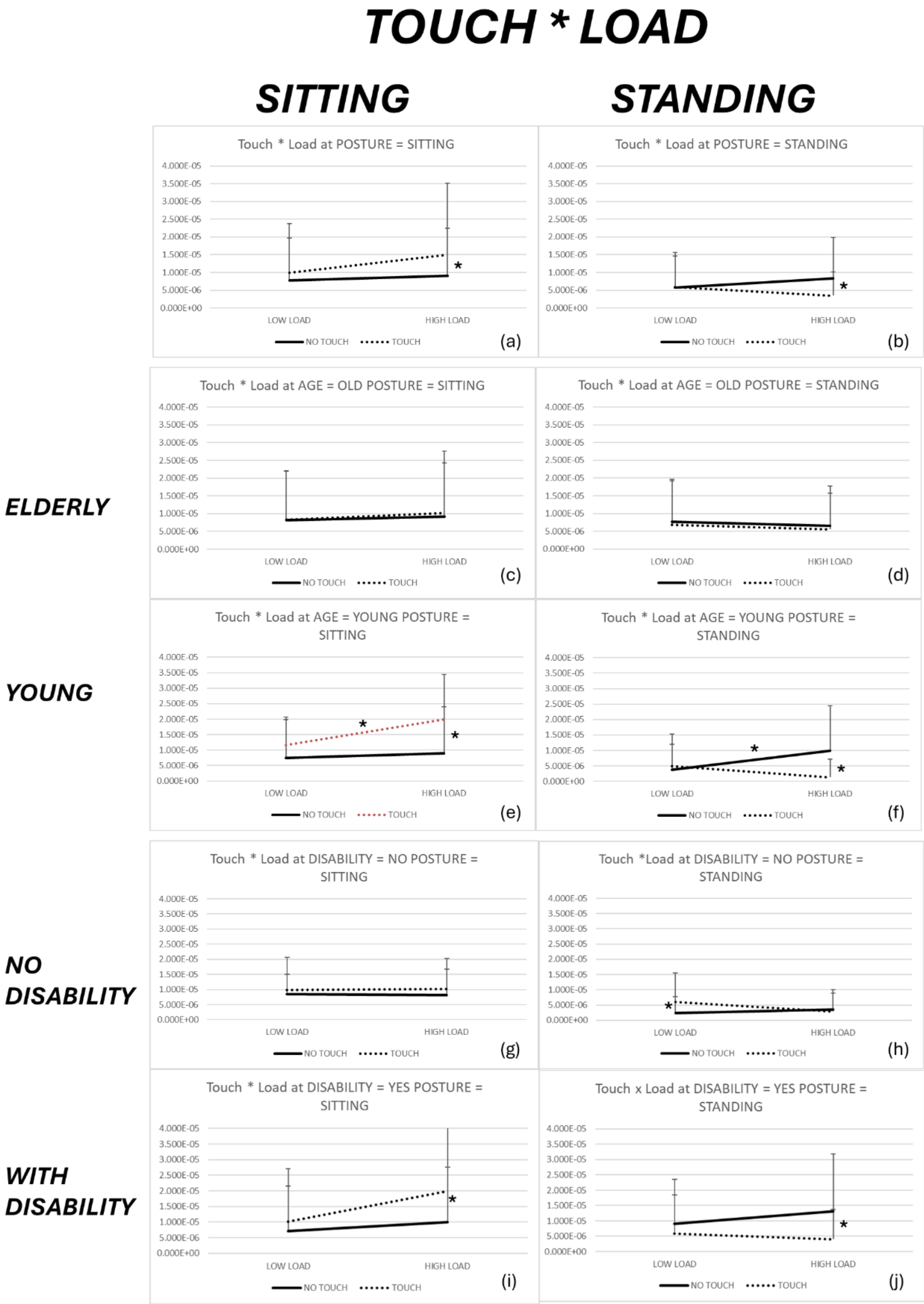


*Figure 5.8. Interaction of touch and load under different postural conditions. The graph illustrates the effects of touch (with (dashed line) and without (black line)) and load (low load vs. high load) on the dependent variable (e.g., HBO concentration levels) across the two postural conditions (sitting and standing). Significant effects are marked with an asterisk (*p < 0.05). Please refer to the main text for a full comment of the picture.*

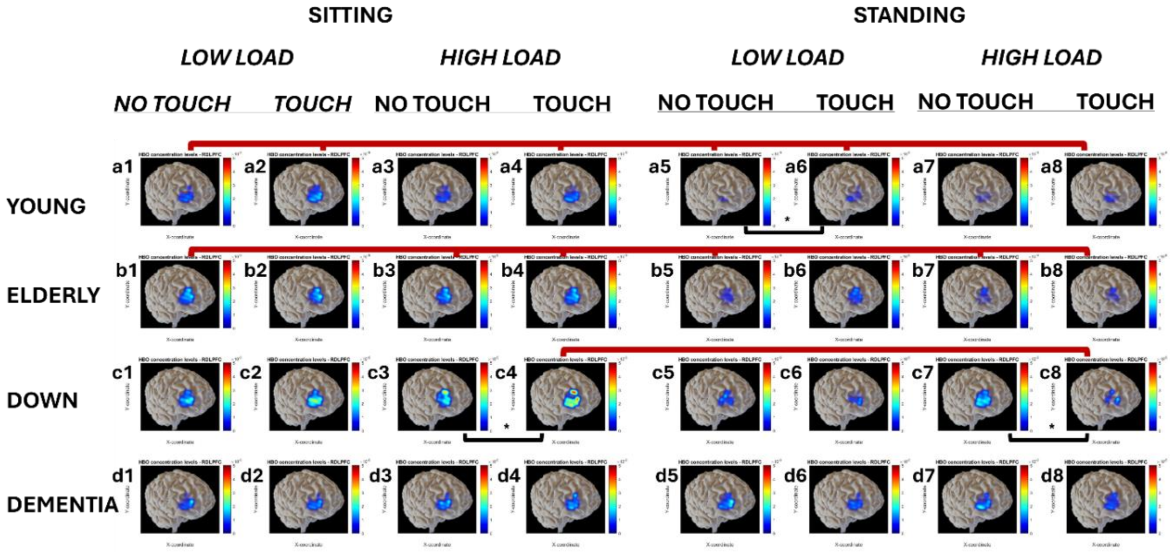


*Figure 5.9. Right dorsolateral prefrontal cortex heatmap. In this, we reported the topographic representation of HBO concentrations levels in the right dorsolateral prefrontal cortex. The graphs report the average activation for each population in the eight different experimental conditions. Red brackets indicate statistically significant effects of posture. Black brackets refer to statistically significant effects of touch. Significant effects are marked with an asterisk (*p < 0.05).*

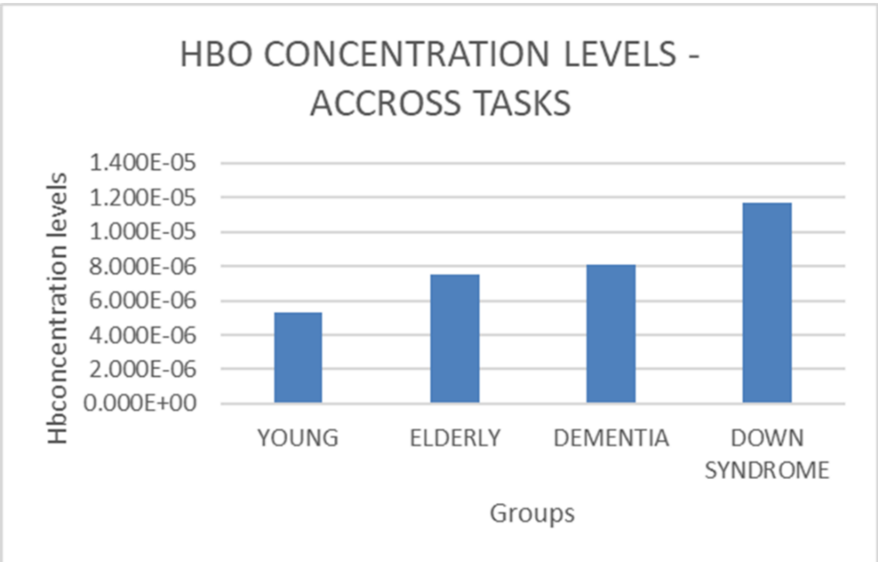


Figure 5.10. Group average HBO concentration level across all conditions. The figure illustrates the average HBO concentration level for each group of participants regardless of the task condition. HBO concentration levels increase with age and disability.

5.5 Discussion

In this chapter, we aimed to address the theoretical hypothesis introduced in Chapter 4, where we explored the literature on how sensorimotor tasks, such as maintaining posture, influence cognitive resource allocation in the frontal lobe. We hypothesized that sensorimotor disruptions, like those observed in older adults or individuals with developmental disabilities, could further affect this allocation. Given the evidence that touch can improve postural stability (Jeka, 1997), we proposed that providing haptic feedback might reduce the mental load of sensorimotor tasks, freeing up cognitive resources for higher-order cognitive tasks. This in turn would result in touch-driven modulation of frontal lobe activity.

The results presented provide a preliminary look into the role of sensorimotor tasks and touch-assisted facilitation in the allocation of cognitive resources. Consistent with our hypothesis, we found that: a) different postural tasks result in varying levels of mental activity, and b) touch, in certain circumstances, modulates the concentration of oxygenated haemoglobin (HBO) in the right dorsolateral prefrontal cortex.

Mental Workload and Postural Tasks

Our results show that different postural conditions are associated with distinct HBO concentration levels in the RDLPFC. Specifically, HBO levels were higher during sitting compared to standing, with this difference being statistically significant in young adults and elderly individuals without disabilities. A similar trend was observed in those with disabilities, including individuals with dementia and Down syndrome, aligning with findings by Almulla et al. (2020), which reported higher mental activity in the motor cortex during sitting compared to standing.

Touch Modulates Mental Workload

Touch also influenced HBO concentration levels during dual sensorimotor and cognitive tasks. Touch generally reduced HBO levels during the standing task, while increasing them during the sitting task. Notably, these divergent effects were more significant when the postural task coincided with a harder cognitive task, suggesting that touch has a stronger impact when cognitive resources are more strained. The largest differences between touch and no-touch conditions were observed in young adults (both typically developing and those with Down syndrome) and in individuals with disabilities (Down syndrome and dementia). Among these groups, only the Down syndrome population showed significant effects of touch, which is notable given their lower scores on the Tinetti scale.

No Cognitive Load Differences in HBO Levels

Contrary to expectations, no significant and consistent differences in HBO levels were observed between the easier and harder cognitive tasks, despite performance analysis showing that the harder tasks took longer to complete (especially in individuals without disabilities). The absence of differences in HBO levels may be due to varying task pacing, with harder tasks requiring more time and possibly prompting different resource allocation strategies. The design of the cognitive task clearly represents a limit of the current study.

Interpreting Mental Workload Directionality

All together these findings support the hypothesis that postural conditions can affect the execution of higher cognitive tasks, especially in terms of mental workload in specific areas like the RDLPFC, which is involved in attention and executive functions. The results also suggest that in populations with disabilities, haptic feedback during tasks modulates resource allocation in the frontal lobe. However, these findings do not clarify whether changes in HBO concentration should be interpreted in terms of increased frontal load or rather increased frontal capacity available to engage with a task. As hypothesized in Chapter 4, touch may reduce mental workload, freeing resources for the accomplishment of cognitive tasks. In this paradigm, modulation of HBO concentration levels could have a dual interpretation, increased HBO levels in the RDLPFC could reflect either increased frontal load or increased frontal capacity, while decreased levels could indicate reduced workload or diminished resource availability.

In this dual perspective, with a reference to the HBO variations observed in the postural task, with higher HBO concentration levels during the sitting task, we could hypothesize that sitting task could be reducing the cognitive load associated with the sensorimotor task leaving more resources available that are in turn allocated in the RDLPFC for the execution of the task. In this perspective the observed increased level of HBO concentration levels would be interpreted in terms of increased resources available rather than in increased load. In this sense the data should be observed and interpreted not in terms of cognitive load reduction but rather in terms of cognitive facilitation. Another yet opposite explanation is that the sitting task we proposed was actually more challenging than the standing task, and that would be explained by the increase in HBO concentration level. We asked the participants to adopt a sitting position quite unnatural, as they were instructed to sit while maintaining an upright posture with the specific requirement of not leaning on the chair's backseat. In addition, the participants were instructed to elevate their not-dominant arm to hold the tablet high enough to intersect the eyeline. We can hypothesize that this task may resulted as more challenging than maintaining a close feet stance and thus resulting in increased frontal lobe activity. With respect to the population with disability – people with Dementia or Down Syndrome -, the results presented here did not show consistent differences due to postural conditions but contemporarily showed higher HBO concentration levels that the participants with no disability. This could be interpreted as a sign of increasing difficulty in the standing task for those participants that also had lower score in the Tinetti postural scale.

With a reference to the touch effect on HBO concentration levels, the divergent effect according to the postural task, observed especially in the population with DS could also lead to different interpretations.

If we interpret the data in terms of increased resources available, the provision of touch would be responsible, in the sitting condition, of increased frontal capacity for the task accomplishment, while in the standing task it would result in a reduced recruitment of cognitive resources. If, however, we embrace a cognitive load reduction perspective, during the standing tasks – harder cognitive tasks touch is determining a reduced frontal load while in the sitting task touch would be adding load to the whole task. It could be argued that in the sitting condition the provision of a haptic feedback could be adding a perturbation to the postural task rather than reducing the challenging associated with it. This could be the results of an unnatural posture adopted by the participant with the back touch being an added challenge to this maintenance of the upright posture. In the context of the unnatural sitting task proposed, the provision of the back touch resulted as ineffective in mitigating postural demands on cognitive resources. In the context of sitting a similar result was found in Baer et al, (2022), where the provision of a sensory feedback that promoted healthier neck posture resulted in increased cognitive load and lower performance results. Similarly, in our results the haptic signal in the sitting postural task may have prompted postural readjustment that consequently determined an increased mental workload.

If we refer to the standing postural task, we have observed a general trend of HBO concentration levels reduction in the population with disability and especially in the context of harder cognitive tasks. In line with the cognitive load reduction perspective, we could argue that in the close feet standing task the provision of haptic assistance probably contributed to facilitating the postural task (preventing fall or excessive body sway), leading to an overall reduced mental workload. In the context of the population with Down Syndrome this interpretation would be consistent with the improved performance registered in the touch condition, during harder cognitive tasks.

Also, the differences acknowledged between postural conditions in terms of HBO concentration levels in the RDLPFC may subtend a different role of this specific area in relation to the posture assumed. As such, differences between sitting and standing may not be interpreted in terms of higher or lower recruitment but rather in terms of different recruitment. As such, the touch effect observed could also be indicative both of increased frontal load or rather of reduced frontal load and increased resources or decreased capacity in other brain area. Our study only measured HBO levels in the RDLPFC and as such the investigation of other brain regions may help in the interpretation of the results.

In relationship to the direction of the HBO concentration modulation, it should be noted that in this study we found higher HBO levels in Down syndrome and dementia populations compared to young and elderly groups. This finding is in partial contrast with what is reported in literature. Research using fNIRS in populations with dementia and Down syndrome is limited and reports mixed results. In dementia, some studies show increased or decreased HBO levels during dual cognitive-motor tasks compared to control groups. In Down syndrome populations, fNIRS studies have reported lower activation levels than age-matched controls. This was interpreted as a difficulty in resource allocation. These differences may be particularly related to the specific area we considered in this study, the right Dorsolateral Prefrontal Cortex. However, the discrepancy observed between our results and what reported in literature should merit further considerations.

5.6 Limits of the study

This study comes with some limitations. A clear limitation of this study is represented by the unbalanced size of the samples. Especially in the population with disabilities (Down Syndrome, Dementia) the number of participants was quite low in comparison with the groups of people with no referred disabilities (TD – ELDERLY). Future studies should expand the number of participants with disabilities.

Another clear limit is represented by the design and nature of the cognitive task we proposed to the participants. We designed two types of Schulte's table. Schulte's table's numbers order was customized to modulate the difficulty of the cognitive task with a backwards order representing the easier cognitive task and the alternate order (25-1-24-2-…) for the harder cognitive task. The results showed that the easier and the harder Schulte's tables referred to two different temporal domains as demonstrated by the increased time effort needed to accomplish the harder task. This difference in task duration was not mirrored by any significant difference in the fNIRS signal. This absence of difference withholds any disambiguation of the directionality and interpretation of on the modulation of the HBO concentration levels.

A possible explanation is that the Schulte's table is a self-paced task; each participant can control the rhythm of the task accomplishment. This can interfere with the subjective allocation of resources in the RDLPFC, with the mental workload possibly being diluted in a longer time dimension. To this we should also add that the Schulte's table we proposed together with the numerous tasks' repetition could have brought into the analysis a not-neglectable process of accommodation, driving the tasks to be progressively easier to be accomplished. Future research should integrate cognitive tasks with different level of difficulties requiring however similar temporal pressure and reduced possibilities of accommodating to the task difficulty.

5.7 Conclusion

In conclusion, what emerges from this exploratory research is that posture differences are associated with different mental workload, and that touch is shown to modulate frontal lobe resources allocation under specific circumstances and in specific groups. All together these results reinforce the need to highlight the involvement of the sensorimotor domain in the context of higher order cognitive performances and subsequently how assisting the sensorimotor processes can in turn free up cognitive resources that can be allocated elsewhere. Touch resulted as a possible conduit for the modulation of resources allocation in the frontal lobe. As such the specific effect of touch on cognitive load merit further investigation. The experimental paradigm we implemented here could be expanded and fine-tuned in order to explore more accurately the relationship between posture and cognitive performance in the population with or without disability. In particular, research should scope the role of touch or other sensorimotor facilitations in mitigating posture and motor coordination and contextually, whether integrating sensorimotor adjustments can also lead to enhanced performance and learning outcomes.

Such an acknowledgment could lead to multiple applications. In the context of DD, it could foster the design of specific interventions or assistive tool focused on the reducing the impact of sensorimotor challenges in the learning process or in the performances during the execution of cognitive tasks of increasing difficulty. In the context of the healthy population, acknowledging a strict relationship between the postural task and the cognitive performance could also foster the development of strategies to assist sensorimotor coordination to favour studying or working performances.

CHAPTER 6 - GENERAL DISCUSSION AND FUTURE DIRECTIONS[3]

6.1 Introduction

In this chapter we try to connect the results presented in the thesis to see what organic picture of FC emerges from them and then comment on this picture. To achieve this goal, section 6.2 of this chapter is set to summarize the results, and the conclusions reached by each single chapter (chapters 2, 3, 4 and 5). There we showed that a) FC can be a mean for users to participate at a level higher than what the ideomotor hypothesis would suggest and b) that touch based assistance – such as that provided in FC- can be a means to reducing the sensorimotor cognitive-workload and a way of freeing up cognitive resources. Then the second section is set to unify the results obtained to provide a new framework from which FC can be interpreted and reclassified as an Assistive Technology that a) intervenes both at motor and cognitive level and b) has rehabilitative-habilitative purposes. Sections 6.3.1 and 6.3.2 will expand the consequences of this renewed FC interpretation. Specifically, section 6.3.1 goes further into framing FC as a developmental tool, while section 6.3.2 explores the role of touch for rehabilitative and assistive purposes beyond pure FC applications.

6.2 Summary of results

The results reported in chapter 2 and 3 have proven FC to be, accounting for inter-individual variability, a means to the co-creation of written outputs. This suggests that users are engaged not only from a motor standpoint but also linguistically. Thus, FC generated outputs are not the product solely of facilitators' influence on users' pointing gestures. The provision of a haptic support from the facilitator does not prevent the users from contributing to the generation of linguistic contents. In chapter 2, through quantitative linguistic methods we found a constant stylistic mark on texts written by single users with different facilitators, indicating their engagement at a word or lexical level. In chapter 3, through the analysis of pointing and eye-tracking movement we found that some users clearly demonstrate literacy skills, exhibit signs of linguistic contribution to the generation of texts (facilitation from the linguistic context) and also exhibit reduced indicators of the facilitator's cueing. Acknowledging the user's contribution beyond the motor component is the first milestone of this thesis. The scientific literature has for long negated to FC users any literacy skill (Beals, 2022). Together, chapters 2 and 3 reported for some users the ability to read and generate linguistic content through Facilitated Communication. At the same time, our results equally clearly indicate that (a) the facilitators are providing their contribution in the generation of the written output and (b) there is a

[3] Part of the work presented in this chapter is also reported in Nicoli, G., Mitra, S., Pavon, G., Grayson, A., and Emerson, A. (2023a). Touch may reduce cognitive load during assisted typing by individuals with developmental disabilities. *Frontiers in Integrative Neuroscience*.

wide range of variability of the levels of contributions expressed by users – this directly implies various levels of support and contributions from the facilitator.

In chapter 3, we posited that the contribution provided by FC users can be set along a continuum from no contribution to fully communicative contribution, passing through the motor engagement only (ideomotor hypothesis) and linguistic involvement in addition. Given the methodological difficulties in directly investigating the communicative participation of users, our research goal has addressed the level of users' linguistic engagement as the next level above motor contribution only. In the context of the co-created nature of FC outputs, we have hypothesised that facilitators provide a scaffolding structure that the users can gradually fit into and add their contribution at word-level or at sentence level. In the former case, users would complete words prompted by the facilitator, in the latter they would contribute through lexical choices given a syntactic framework (see chapter 2 discussion).

In the second part of this work, chapter 4 and 5, we proposed a theoretical explanation for why touch could facilitate people with DD in the accomplishment of a typing task.

We have seen that the FC dynamic can be explained as the sum of various components: the ideomotor influence of the facilitator, their provision of a linguistic model by scaffolding language either at word or sentence level and users' motor and in some cases linguistic participation. Within this framework we hypothesized that the provision of a haptic support can be a conduit for sensorimotor facilitation. In chapter 4, we connected different strand of research (cognitive-motor interaction, light touch paradigm, sensorimotor and executive deficits in people with DD) to show that in the context of people with DD, the sensorimotor issues associated with this population (difficulty in maintaining balance, motor planning and motor coordination) can hamper the execution of the motor component of the typing task (Torres, 2013a; Bieć et al., 2014; Ament et al., 2015; Doumas et al., 2016; Brugnaro et al., 2020; Klotzbier et al., 2020). The literature on cognitive-motor interference shows that postural and motor tasks are cognitively demanding and compete for the same limited cognitive resources also required for the execution of higher or supra-postural cognitive tasks (such as generating text) (Fraizer and Mitra, 2008c; Al-Yahya et al., 2011). In the context of the DD population, the reported struggles with maintaining the body's balance while coordinating a reaching arm movement can be more cognitively demanding. Thus, this need for more mental resources can have a detrimental effect on the supra-postural/higher cognitive task which would have less resources available. We noted that this detrimental effect would have a much bigger impact given that people with DD are reported as also having a limited level of cognitive resources (Daunhauer and Fidler, 2013; Demetriou et al., 2019). The literature on the light touch paradigm has shown that providing a haptic support can improve the balance performance by augmenting the information available to guide postural control (Jeka, 1997, 1997; Baldan et al., 2014).

With this background, we hypothesized that, in the context of DD, the provision of a haptic support during a typing task, similarly to what happens during FC, may reduce the cognitive load associated

with the sensorimotor task (maintaining upright posture and coordinating the pointing movement) while leaving more resources for the accomplishment of the linguistic task (text generation).
In chapter 5 we tested this hypothesis with a preliminary experiment. The results provided by the fNIRS analysis have shown that (a) different postural conditions lead to different mental workload and (b) the provision of touch does have an impact on the cognitive load although in diverse ways depending on task conditions. The results presented should be considered as a preliminary exploration of the effect of touch and given the methodological limitations, their explanatory power is low.

6.3 A renewed framework of FC

The work presented here had the purpose of creating room for a middle ground where FC could be redefined and re-explored free from pre-concepts or pre-emptive fixed positions. Our work has tried not to address FC from the communicative angle but from a levels of engagement perspective, looking for signs of users' engagement or participation below the pure communicative level but also expanding the motor and linguistic level. Also, we tried to derive a theoretical hypothesis that could account for the role of touch-support beside the pure ideomotor one.

The results presented in 2 and 3 have shown that users are to some extent and at different inter-individual levels participating in the generation of linguistic content. Accounting for individual differences, these results suggest that there can be some utility in using FC.
We have proposed that FC can be a conduit for co-construction of text where both the user and the facilitator are actively engaged in contributing to the typing task. We have then proposed the hypothesis that facilitators may scaffold and model language construction to allow users to progressively add their contribution either at morphological or lexical or syntactic level. On this basis, we have proposed that there is a possible developmental value to such operation. Through the scaffolding and modelling effort provided by the facilitator, users may progressively develop, expand and strengthen their literacy and typing skills. To this point, we cannot say whether the demonstrated linguistic participation of users, therefore their linguistic skills were caused or were just tangential to the use of FC. We will have the chance to explore this point in the next paragraphs. To this hypothesis, we have added in chapter 4 and 5 a theoretical proposal for why touch can work as a mean towards sensorimotor facilitation and how this facilitation can free up resources that can be orientated to the linguistic task.
All together these considerations lead to a completely renewed perspective of FC that updates the classification of FC in the context of Assisted Technology, described in Chapter 1.
In Chapter 1, we proposed a classification of FC within the Assistive Technology domain in the light of the existing literature and uses of the technique. The results described in this work suggest a change in the classification of FC as an AT technology. While we could still refer to FC as a form of

Augmentative Alternative Technology and as a low-tech Assistive Technology, the results and their interpretation provided in this works call for a renewed perspective on the levels of impairment the technique is set to assist and the intended purpose of the assistive tool.

In Chapter 1, based on the existing literature, we defined FC as an assistive tool that aimed at only providing motor facilitation to its users, as proposed by Biklen (1990). The results and the considerations presented in this work however suggest that FC is also a means of cognitive facilitation, and this in two different but simultaneous ways.

We proposed that the co-creative effort of facilitators in the generation of linguistic output, described in Chapter 2 and considered in Chapter 3, can be intended, in a developmental perspective as a form of linguistic modelling and scaffolding. As such, we suggested that facilitators would provide syntactical, or lexical context that users can progressively insert into to co-construct a linguistic output. This modelling and scaffolding contribution on behalf of the facilitator would, on one side, reduce the user's cognitive demands associated with linguistic content generation, and enable better focus on specific segments of sentence construction. On the other side, it would expose the user to well-formed linguistic structures possibly supporting the development of linguistic skills.

Secondly, as described in Chapter 4, we hypothesized that the provision of haptic support would facilitate the accomplishment of sensorimotor task co-occurring with the typing task, thus maintaining an upright posture, modulating postural perturbation due to the reaching arm gestures, and supporting visual search. We have shown that maintaining an upright posture, especially in the context of developmental disabilities, draws on cognitive resources. Facilitating the sensorimotor task therefore would free up resources that can be allocated for the typing task.

Finally, the intended purpose of the technique has to be reimagined in light of the results described here. If we embrace a developmental perspective, FC could be reinterpreted as an assistive tool which has the goal and the potential to foster the development of linguistic and communicative skills, acknowledging the technique as an habilitative-rehabilitative tool rather than a lifelong assistive tool. We think that this renewed perspective can create the condition for a middle ground where FC can be explored free from extreme positions and pre-concepts, a place where FC applications can be updated and modified safely, and a ground that can exploit possible FC benefits -to foster newer and improved assistive strategies for people with developmental disabilities.

This renewed classification suggests different benefits in adopting FC as an assistive tool. It endows FC with a developmental and habilitative-rehabilitative purpose and simultaneously mitigates the controversial spikes for long associated to the technique because it pushed the goal of users' communication as the final stage of a sequential developmental process. Rephrasing FC in the context of a developmental perspective and the co-construction of texts, and in the light of the proposed cognitive-facilitation role of touch represents the major outcome of this thesis. In the following paragraphs we explore further into the consequences of this renewed perspective.

6.3.1 FC: co-creation and developmental aspects

The reclassification proposed highlights the developmental perspective that reimagines FC as a tool that can contribute to the gradual and progressive acquisition of linguistic and communicative skills. The results presented in Chapter 2 and Chapter 3 showing clear linguistic contribution on behalf of some FC users, suggest that FC may have fostered the emergence of linguistic competencies in at least some of the user with DD that participated to our research. While we have no means to discriminate whether that evidence of users' literacy skills or linguistic contribution are the developmental results of years of using FC or they are just tangential or even not related to its use, we can hypothesize that constant practice in the generation of linguistic content may have contributed to the emergence or reinforcement of some of the linguistic skills we have acknowledged and described in our results.

Whether this learning is purely statistical in its nature -and as such it registers users' ability to infer statistical features from the contextual environment but does not indicate literacy skills (Beals, 2022)- or rather mirrors users' linguistic development will probably continue to be a matter of debate.

In chapter 3's discussion section we hypothesised a possible account for why the linguistic contribution exhibited by the users does entail some linguistic competence. However, even if the learning observed was purely statistical and unlinked to any linguistic content, the developmental trajectory accomplished by users should not be discarded as a tangential by-product of the application of FC but rather it should be acknowledged and given credit as an accomplishment and possibly supported and integrated.

If the users' development were linguistic, we hypothesized that learning passed through the exposure to a structured model of language that users progressively incorporated and controlled. The diverse levels of users' engagement described in Chapter 3 can possibly mirror the different developmental phases the user had to pass through. We hypothesised that in the initial phase the facilitator provides a linguistic model that progressively turns into a scaffolding. This scaffolding can initially be at word level: here users may be involved in the completion of words. Then the scaffolding can turn into a sentence level: here users are involved in the generation of lexical choices within a formed syntactical structure. In this context, users' development can be seen as the result of facilitators' linguistic scaffolding and its progressive fading. As such, these achievements could be the results of a developmental trajectory that started with a consistent involvement on behalf of the facilitators.

This hypothesis has some resemblance to the talking typewriter experience we introduced in Chapter 1 (Goodwin and Goodwin, 1969). In that context, the users exhibited the development of linguistic skills after being trained to use a machine that guided them during typing by allowing them to press just the correct key. Similarly, the model presented by the facilitator and possibly their guidance towards specific sequences of characters to generate linguistic output may have fostered users' learning.

If the hypothesis that FC led to the development of literacy skills held true, we should note that, looking backwards, the development observed in users happened with the facilitators being not aware of their scaffolding and development-fostering role. Facilitators are reportedly not aware of providing an active contribution to the generation of text, and FC has mostly been used as a communicative tool rather than a developmental one. We have seen that the spurt of FC and its rapid diffusion mostly relied on the sudden unveiling of unexpected literacy skills. A perspective that hardly matches with a developmental process. As such, we have to conclude that if there were a learning process that was an accidental by-product of the application of FC.

If we adopt a forward perspective instead, adopting a developmental perspective would dramatically change our understanding of FC and consequently its application. FC and FC like techniques can be re-evaluated as conduit for the development of linguistic and literacy skills.

Adopting a developmental perspective in the context of FC adds a temporal dimension to the technique. As seen in Chapter 1, the success and the rapid diffusion of FC was consistently due to the lack of a temporal dimension as the provision of touch-based assistive techniques immediately unveiled and awakened hidden linguistic competencies. Parallelly, the major scepticism around FC emerged as an objection to this sudden revelation of communicative competencies.

In the light of the evidence that users can possibly provide their contribution to text generation and in the light of the theoretical hypothesis that touch assistance can provide a cognitive facilitation by reducing the concurrent sensorimotor task mental workload, we can imagine a renewal of touch-based assistive techniques as means towards the development of linguistic skills. As a consequence of this renewed approach the facilitators' role would change significantly. Their scaffolding and co-creative effort in text generation would emerge from implicit to explicit and as such it could be guided by precise, scalable and measurable learning goals.

At this point, and especially in the light of the developmental perspective adopted here, one could question the communicative goal associated with FC. In no point during our research did we aim to address whether the messages produced through FC did mirror the communicative intention of the user. The experimental design did not have the power to investigate this. As such, in this work we could not provide any judgement about any communication intention or success on behalf of the user. We also cannot exclude whether in the continuum that goes from no contribution to fully autonomous communication, some of the users' (especially of those who exhibited major signs of linguistic contribution) more relevant stylistic marks and FC-independent literacy competencies, were indeed contributing also at a communicative, information-passing level. It is clear that while the written output keeps showing signs of facilitator co-contribution, this would call for some prudence in interpreting and reliably considering FC users as the sole sources of the texts produced. Retrospectively, looking at the production of experienced FC users, we suggest that further evaluations of single users' contribution during text generation and more strongly the assessment of

FC-independent linguistic competencies would provide a much clearer picture also on how productive the use of FC could be.

It could be argued that an AAC technique that cultivates co-authorship may not foster the users' autonomy and independence. This issue of autonomy, alongside that of authorship, has often been central to the debate on the utility of FC (Wehrenfennig et al., 2008; Saloviita et al., 2014; Schlosser et al., 2014). These two issues should be considered and addressed separately as they may reflect two different goals. This research addressed the issue of authorship and the possibilities of increasing the AAC users' communication options. The results clearly show that a technique like FC extends users' ability to express themselves linguistically. A co-authorship framework does not guarantee independence, which may reach different levels in the case of different users. These differences may originate in the users' inherent characteristics or in the stage of development in FC training. Over time, significant autonomy of expression may be achievable for some, but not for others. In both cases, however, using an AAC technique fostering co-authorship may provide developmental and quality of life advantages through increased communication options that might not otherwise become available.

In conclusion, the first part of this work calls for a dual approach towards FC that changes in relation to the perspective embraced: retrospectively to analyse past uses of FC, or to shape future uses of FC in a forward perspective.

A retrospective evaluation of FC has to consider the wide inter-individual variability. It is not possible to uniquely evaluate the efficiency of the technique by setting aside all the individual differences. Our results have shown that, along the continuum between no contribution to full contribution, FC users occupy different spots exhibiting different competencies. This work has shown that for some users FC is an effective tool for co-participation at a linguistic level in the generation of written output. It has also shown that for some other users this level of participation is not yet achieved or at least could not be detected through our means of analysis. Increased participation could have been the progressive result of a developmental trajectory. These results alone cannot verify whether for those users exhibiting higher levels of participation the written output also mirrored their communication intent. For that, our work invites attempt to verify the existence of literacy skills outside the FC environment.

If we evaluate FC orientating towards the future, this works calls for a re-interpretation of FC in a developmental perspective. Our results suggest that we should postpone the primary goal of autonomous communication making it the final outcome of progressive steps of a learning process. A progressive, guided development of literacy competencies would therefore call for a more structured and goals-directed approach towards the application of the technique, inviting facilitators to adopt a more controlled and conscious approach to their role and their function within the communication exchange.

We are aware that this perspective would change the approach towards FC-like techniques. Removing the promise of an immediate communicative interface with the FC user would reduce the appeal of the technique as it undermines its primary and more rewarding goal. Adopting a developmental perspective would in turn set phases of progressive learning pushing communication as the final and progressively achieved goal of the intervention.

It should also be noted that we cannot definitively define communication as a sole means of exchanging information. In our daily experiences, we encounter numerous communicative situations where conveying information is not the primary goal of our communicative effort. Communication can also be understood as a social act (Duchan, 1999), serving as a vehicle for participation in social activities and integration within social groups. As such, it functions as an instrument for building and maintaining social connections and fostering communal bonds.

Where an individual with DD who has cognitive and sensorimotor deficits is physically assisted, either by touching the shoulder or the arm, it should not be surprising that the facilitator has an influence on the action movements. A motor-impaired patient being physically assisted to walk would not produce movement that is free of the facilitator's influence. The patient's gait parameters and trajectory pattern would vary as the facilitator changed, and any kinetic-kinematic analysis would reveal the significant extent of the facilitator's contribution. Although such locomotion would not be independent motor output, the process of assisted walking could have significant learning and rehabilitative benefits. This would be true even if fully independent walking was never recovered, so long as the assistance provided enabled the patient to make some contribution to their movement.

This important point is clarified by an analogy drawn in Wertsch's (1984) commentary on Vygotsky's (1978) concept of the zone of proximal development. Vygotsky's concept refers to actions that a learner can currently perform only with teachers' or more advanced peers' assistance. Such assistance can scaffold the learner's development, but only if it has certain key characteristics beyond producing the outputs in question. Wertsch used the example of a child being helped by an adult to divide 124 by 23. If the adult guides the child using leading questions such as "how many times will 23 go into 124?" and "what do we do with the remainder?", and so on, their assistance would be of a profoundly different kind to that of another adult who tells the child to write specific numbers in specific locations on the paper. The outcome in both cases would be that the child writes the correct answer, but only the former type of assistance would have served as a scaffold for learning and therefore been of developmental value. The key point is whether the assistance enabled the learner to have a meaningful role in text generation that they alone could not have had.

The two types of assistance discussed by Wertsch are important to how we understand assisted typing techniques. If touch only served to provide specific cuing, then the situation would correspond to Wertch's second scenario. The individual with DD would be a conduit for the facilitator's expression. On the other hand, if touch reduced the cognitive load of even a partial contribution from the individual with DD, the effects on the person's development, quality of life, connection to carers and

sense of self-worth could be impacted positively. Whether the individual could generate, or develop to generate, typed text independently would not be the sole determinant of the value of practising and better understanding touch-assisted typing.
As such, adopting such techniques while being less capable in terms of information passing may be a fruitful conduit for creating and originating social interactions with pairs and to participate and engage in social activities.

If the developmental perspective is adopted and applied to improve FC applications, the experimental framework presented in this thesis could be adapted to monitor the literacy progression of users over specific time periods. This can be achieved by analysing the stylometric properties of the text produced and examining behavioural measures during the typing task, such as inter-keystroke intervals (IKI), eye-tracking indicators of participation, and pointing hesitancy. Additionally, if the intervention is designed with a developmental focus, FC training could also incorporate the message passing task as a central component, along with other literacy development strategies that do not necessarily rely on FC. Moreover, tasks like message passing or other non-FC-dependent activities could provide valuable insights into the development of literacy skills.

6.3.2 Touch support and cognitive load.

The reclassification of FC opens up to a renewed perspective on the touch-driven dynamic of the technique, recognising for touch also a role in cognitive facilitation. The acknowledgment of this role has consequences that can be extended beyond the sole domain of Facilitated Communication.
Within FC, the touch-driven sensorimotor facilitation can ease up the postural and motor coordinating subtasks associated with typing. This in turn would leave more resources that can be allocated to the linguistic or communicative task. We have demonstrated that FC can be seen as a developmental process in which users through the implicit (retrospectively) or explicit (prospectively) linguistic modelling provided by their facilitator can progressively construct linguistic skills. Within our theoretical hypothesis, easing up the sensorimotor task would leave increased cognitive space to be allocated to the developmental and learning process. With a specific reference to typing, literature shows that in early writers the more is the struggle with the motor component of writing (be it handwriting or typing) the more the linguistic output is affected (Drijbooms et al., 2015). Similarly, in the context of FC attenuating the sensorimotor struggles associated with the pointing gesture could have a positive effect on the concurrent linguistic task.
If we lean outside the perimeter of FC, the application of touch-based support could be expanded and integrated in assistive or training approaches. Many clinicians or therapists reading this work may be familiar with the use of touch during their session to help their clients to foster a focalized attention on the task, provide physical containment or motor guidance (hand over hand). Despite the consistent use of touch during therapy little research have been conducted in this field.

The literature review conducted in this study underscores a significant connection between developmental disabilities and deficits in sensorimotor function, postural control, and coordination (Fournier et al., 2010; Brugnaro et al., 2020). A considerable body of research highlights how children and adults diagnosed with conditions such as autism spectrum disorder (ASD), Down Syndrome, Fragile X Syndrome, and Dyslexia often exhibit impairments in postural stability, delays in the development of both fine and gross motor skills, as well as challenges in motor planning, programming, and execution (Bieć et al., 2014; Ament et al., 2015; Torres and Donnellan, 2015a). These motor difficulties are frequently accompanied by co-occurring limitations in executive functions, a set of cognitive processes critical for goal-directed behaviour, such as attention, working memory, and inhibitory control (Daunhauer and Fidler, 2013; Demetriou et al., 2019).

A pivotal finding from our literature analysis is the recognition that both postural control and executive function compete for the same cognitive resources. This competition implies that when an individual is engaged in both postural and mental tasks simultaneously, it can lead to increased cognitive load or a reduction in efficiency in completing one or both tasks. This is particularly relevant in populations with developmental disabilities, where cognitive and motor demands are often intertwined.

Moreover, studies have shown that even in individuals without diagnosed disabilities, there is a clear connection between posture and cognitive load (Barrra et al., 2005; Baer et al., 2022). Different postures are associated with varying levels of mental workload (Almulla et al., 2020). As a result, some researchers suggest that certain postures may enhance cognitive outcomes or reduce load during task performance. For example, adopting a posture that minimizes physical strain might free up cognitive resources, allowing for better concentration and task execution. Conversely, a posture that demands more physical effort may deplete cognitive resources, leading to decreased mental efficiency (Igarashi et al., 2016; Inagaki et al., 2018; Baer et al., 2022).

In the context of developmental disabilities, as well as in the elderly population, sensorimotor issues can exacerbate cognitive fatigue, especially in situations where cognitive and motor tasks are performed simultaneously. This dual-task interference highlights the importance of considering postural facilitation as a means to improve cognitive performance. By supporting or stabilizing posture, it may be possible to free up cognitive resources that can then be allocated to higher-order cognitive tasks. This theoretical framework suggests that interventions aimed at improving postural control could have significant implications for enhancing cognitive function and reducing fatigue in individuals with developmental disabilities.

Practitioners in the field of rehabilitation frequently observe the impact of posture on task performance, particularly for tasks that require sustained attention or working memory. In many rehabilitation programs, especially those targeting developmental disabilities, a primary focus is placed on ensuring that the child is correctly positioned, often emphasizing the importance of proper seating and alignment to facilitate task completion. However, there is a growing recognition that deviations from conventional postures might reflect an individual's need to adopt a specific posture that is more efficient for the task at hand (Stoffregen et al., 2000). This observation raises questions about whether non-canonical postures, which might appear unconventional, could actually serve as a more effective means for task execution, especially in terms of reducing cognitive load.

Further investigation is required to understand the implications of these non-canonical postures. As indicated by some studies, adopting an unusual posture might indeed result in increased cognitive load, suggesting that there is a complex interaction between posture and cognitive load (Baer et al., 2022). Additionally, the increased body sway observed in individuals engaged in a postural-cognitive dual-task setup might be a form of postural compensation in response to the cognitive demands of the task. This compensatory mechanism could be a way for the body to maintain balance while also managing the cognitive workload (Torres et al., 2013).

Within this context, our research has begun to explore the role that touch, specifically through haptic feedback, can play in mitigating the cognitive workload associated with sensorimotor tasks. The existing literature on the "light touch" paradigm suggests that the provision of haptic feedback can effectively reduce postural perturbations, even when cognitive tasks are concurrently being performed. This finding is particularly relevant in the context of developmental disabilities, where motor and cognitive challenges often co-occur.

One intriguing avenue of exploration is the role of touch in Facilitated Communication, which has historically been a controversial method but can be viewed as an early exploration of how touch might influence cognitive-sensorimotor tasks. While FC is much more than just postural facilitation, our work suggests that touch could serve as a facilitator of cognitive performance by providing postural support that reduces the cognitive load. This, in turn, could enhance the efficiency and effectiveness of cognitive tasks, particularly in individuals with developmental disabilities.

The findings from this study encourage further exploration of the role of postural facilitation in enhancing cognitive performance. This could be achieved through improved task outcomes, reduced load, or by facilitating the training and development of specific skills. The reinforcement of postural balance could be addressed through targeted training programs or the development of assistive tools that provide real-time postural support. This approach could be beneficial not only for individuals with developmental disabilities but also for the elderly population, who often face similar challenges with sensorimotor function and cognitive load. Moreover, future research exploring the links between posture and cognition could have broader implications for the general population. Understanding how different postures influence cognitive workload could lead to the development of strategies aimed at improving study and work efficiency, even in individuals without diagnosed developmental disorders. For instance, ergonomic interventions or posture-based training programs could be designed to optimize cognitive performance and reduce fatigue in various settings, such as educational environments or workplaces.

Our research has confirmed two key findings: (a) differences in posture lead to variations in mental workload, and (b) the provision of touch, particularly in the context of developmental disabilities, modifies frontal workload, potentially reducing the cognitive demands of tasks that require sustained attention or working memory. However, it is important to acknowledge that the use of external haptic feedback, such as touch, raises questions about authorship attribution and the extent to which the individual is independently performing the task. Despite these concerns, our work demonstrates that touch can serve as a facilitative tool that not only supports postural stability but also acts as a conduit for learning and the development of skills. The ultimate goal of such interventions is to promote autonomy and independence in individuals with developmental disabilities.

At the same time, the principles of touch assistance could be adapted and applied to the development of technological tools designed to support postural tasks. These tools could range from simple devices that provide real-time feedback on posture to more sophisticated systems that integrate haptic feedback with cognitive training programs. Such innovations have the potential to enhance the quality of life for individuals with developmental disabilities and the elderly, while also contributing to our understanding of the intricate relationship between posture and cognition.

In conclusion, this study underscores the importance of considering postural facilitation as a key component in the enhancement of cognitive performance, particularly in populations with developmental disabilities. By exploring the interplay between posture, cognition, and touch, we can develop more effective interventions that improve outcomes, reduce fatigue, and support the overall development of individuals with unique cognitive and motor challenges.

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APPENDIX I – DATA ACQUISITION

Motion data are collected from Codamotion CX1 motion sensors using ODIN software. This system uses active infra-red emitters placed on the body captures position data in real time using 2 to 4 measurement units and some active markers. The measurement unit is capable of tracking the 3D position of a marker in real time. Three masked linear arrays (MLAs) in each unite combine to measure X,Y and Z coordinates for each active marker. The active marker consists of miniaturized infra-red that flash their own light as opposed to the measurement unit. A masked linear array measures the pattern produced when a flash on the active marker cast a shadow on an array through a grid of lines (mask).

The system register the position of the marker with a 25hz sampling.

It returns a time series where for each timestamp the 3D coordinates are specified, see table I.1. The time series vector were exported and uploaded to MATLAB.

Time	X (mm)	Y(mm)	Z(mm)
	100	150	130
0.02	110	140	140

Table I.1 Representation of raw movement data In the first column the timestamp is displayed. In the second column the value of the coordinate in the x-axis is displayed. In the third column the value of the coordinate in the y-axis is displayed. In the fourth column the value of the coordinate in the z-axis is displayed.

Eye tracking

To capture the participants' eye behaviour, we used SMI Eye Tracking Glasses 2 wireless system and the BeGaze software. The SMI glasses are designed to capture a person's natural gaze behaviour in real time. It provides 60Hz binocular tracking technology with a high-definition scene camera. The BeGaze software allows the processing and the visual inspection of the eye-tracking data. The software automatically detects visual fixations, saccadic movement, and blinks, providing their duration and their 2D coordinates with respect to the frame recorded by the camera built in the glasses. The absence of a specific point of reference determines the need of a manual definition of the AOIs. The software returns a time series were for each timestamp the 2D coordinates are specified together with the eye-behaviour classification (visual intakes, saccade, blink) and the AOIs associated, see table I.2. Fixations and saccades temporal and spatial information together with the associated AOIs were then exported and analysed through MATLAB.

Time	X (px)	Y(px)	Class	AOI
0	100	130	“Visual Intake”	“A”
0.02	102	128	“Visual Intake”	“A”
0.03	101	132	“Visual Intake”	“A”
…				
1.02	110	110	“Saccade”	--

Table I.2 Representation of raw eye-tracking data. The first column represents the time stamps of each eye-tracking event. The second and third columns represent the two-dimensional displacement of eye-position, with respect to the pixels framework of the video generated by the eye-tracking glasses. The fourth column refers to the class automatically assigned by BeGaze software to the eye-tracking event. The software individuates three different classes: “Visual Intake”, “Saccade” and “Blink”. The fifth column refers to the Area of Interest (AOI) associated to each visual intake. AOIs were manually coded by the researcher.

EMG signal

The Trigno Wireless EMG System is a device designed to detect EMG signal. The signal can be acquired through the ODIN Codamotion system. The signal collect data with a 50hz sampling. It returns a time series were for each timestamp the muscular activation (mV) is registered. The data are already synchronized with the motion information. See table I.3 below.

Time	mV
0	123
0.02	112
0.04	130
…	

Table I.3 representation of raw EMG signal. The first column refers to the timestamp of each EMG registration. The second column refers to the millivolt activation registered by EMG detector placed on users’ deltoid.

Typing timer

A customize online tool was created to register keystrokes data. The tool returns an excel spreadsheet where to each timestamp is associated the value of the key pressed by the participant on the keyboard. See table I.4.

Time	Keystroke
10s	"a"
13,2s	"s"
14.1s	"t"
…	

Table I.4 Representation of raw data collected by the typing timer. The first column refers to the timestamp of each keystroke. The second column refers to the label of the key pressed by the user.

Experimental measures

The integration and synchronization of the data collected through the multiple channels resulted in the graph displayed in figure I.1 which represent the timeseries of three consecutive pointing gesture towards the keyboard.

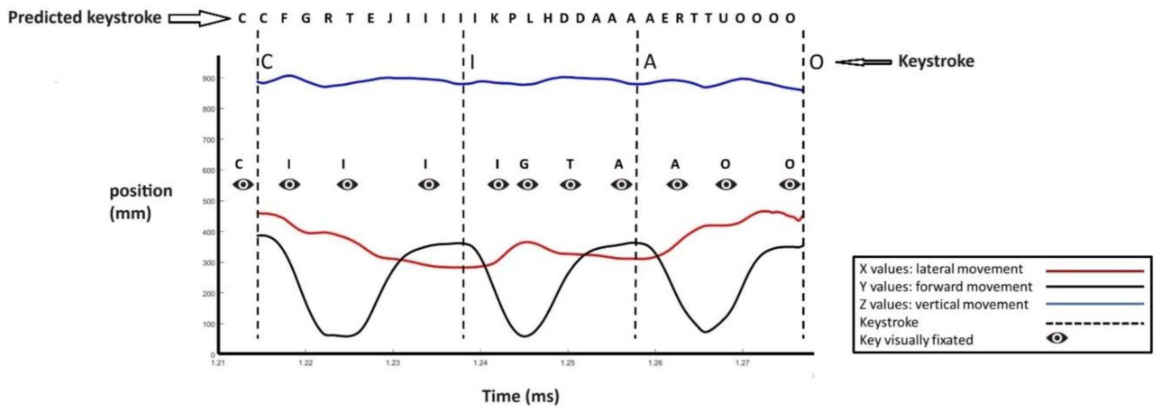

Fig.I.1 Timeseries of three consecutive pointing gestures. The picture exemplifies the integration and synchronization of the data collected (arm movement displacement in the three dimensions, visual fixations, keystrokes timestamps, keystrokes targets). Additionally in the upper part of the picture, the results of the ML learning prediction of the endpoint target are reported.

This data integration served as a basis for the implementation of further analysis (movement profile averaging, tortuosity index, machine learning analysis, the calculation of the distance from the target key of the key visually fixated, the calculation of the probability of each key to occur given the presented character string). In this paragraph we provide a description of the measures we derived from the stream of raw data.

Taking figure I.1 as a reference, we can firstly look at the data originating from the motion system. For each dimension the articulator position is plotted against time. The blue line represents the vertical displacement of the articulator, on a head to feet directionality. The red line represents the lateral displacement of the articulator, from the left to the right side of the keyboard. Finally, the black line represents the horizontal displacement of the articulator, on a chest to keyboard directionality.

The symbols of the little eye, displayed horizontally in the middle section of the picture, indicate user's visual intakes or eye-fixations, and are synchronized with the arm movement data. The characters right above the eye symbols refers to the key fixated for each particular visual intake.

The integration of the temporal data provided by keylogger allowed us to segment the time series into inter-keystroke intervals. The vertical, black dashed line indicate in the time series the exact moment the key was stroke by the participant. On top of the dashed line, figure A.1 report the label of the key pressed. As we can see, the time series report the articulator's displacement during the typing of the last three characters of the word "ciao" (the Italian for hello).

APPENDIX II – MOVEMENT ANALYSIS

Looking at the portion of movement data contained between two consecutive keystrokes, it is possible to recognise a recursive pattern on the y dimension. For this participant, the highest articulator's displacement happens along the y dimension. It is worth noting that after each keystroke, the articulator consistently steps away from the keyboard and return to a position proximal to the user. This is a clear kinematic representation of what in the FC literature is called as the "return gesture" and define a backwards phase of the arm movement to a rest position (usually the chest), before starting the forward component towards the target key.

To allow the creation of a movement profile that integrated and included the arm displacement on all three the dimensions, we calculated, for each pointing gesture, its Euclidean distance. The Euclidean distance computes the distance between two points in a tri-dimensional space. In this specific case, we calculated the square root of the sum of the squared differences in the x, y, and z coordinates between each the 3D arm position in between two consecutive keystrokes and the 3D arm position when the second keys are hit.

In figure II.1a and II.2c (left side of the picture), we show a sample of raw movement profiles between two consecutive keystrokes. In the x-axis we displayed the time component (s^{-2}), on the y axis the spatial component (mm). Zero values in the x-axis correspond to the former keystroke, thus the end of the previous pointing gesture. In the y-axis, the Euclidean distance of the arm from the endpoint target is displayed. As such, zero values in the y-axis correspond necessarily to the moment the user presses the key. Thus, all the Euclidean distance profiles end at 0. It follows that, the higher the value in the y-axis the more distant the arm is from the keyboard.

The intersection between the y-axis and zero value in the x-axis represents the linear distance in the keyboard between the two consecutive keystrokes. For this reason, the former keystroke can originate at (0,0) only when the target of the two keystrokes is the same key (for example two consecutive "a"). Anytime the first keystroke target differs from the second, the first keystroke has y-axis' values higher than 0. The higher the y-axis' value the more distant are the keystrokes' targets in the keyboard.

To facilitate the time series analysis and the averaging and comparison of the movement profiles, we plotted each movement trajectory on a standardised time, so that each movement profile could start and end within an identical time reference. As we can see from figure 5b and 5d (right side of the picture), the duration of each pointing gesture was standardised assigning a t = -10 value to the former keystroke (end of previous movement), a t = 0 value to the moment the users' stroke of the second key. The comparison of figures 3a, c and 3b, d shows how the ratio between the different trajectory changes as it is maximized their relation to a standardized time period.

The resulting graphs (II.1a, II.1b, II.1c, II.1d) show a bell-shaped profile, with the peak value representing the maximal distance from the keyboard and the lowest value representing the closest distance to the keyboard which is reached once the key has been pressed. The comparison between figure 3.3 and figure II.1 shows a reversed profile between the Euclidean distance profile and the y dimensional component (which clearly contribute heavily to the definition of the distance from the keyboard). This is the direct result of the Euclidean distance calculation: endpoint position values are subtracted to all the articulator's position within the inter-keystroke interval. The elevation to the power of two and the following square rooting allows for positive data only. Thus, the reversal of the bell shape.

The movement profile obtained reinforces the visualization of the two separate phasis within the inter-keystroke interval, with a returning phase, the movement stepping away from the keyboard (left side of the bell-shaped profile) and the pointing phase, the movement moving towards the keyboard (right side of the bell-shaped profile).

Given this double partition of the movement profile, it was crucial for our analysis to differentiate the return gesture from the forward gesture. The highest y-axis value, therefore, the major distance registered of the arm from the keyboard, in the Euclidean distance profile was taken as the beginning of the forward movement (see arrows in figure II.1).

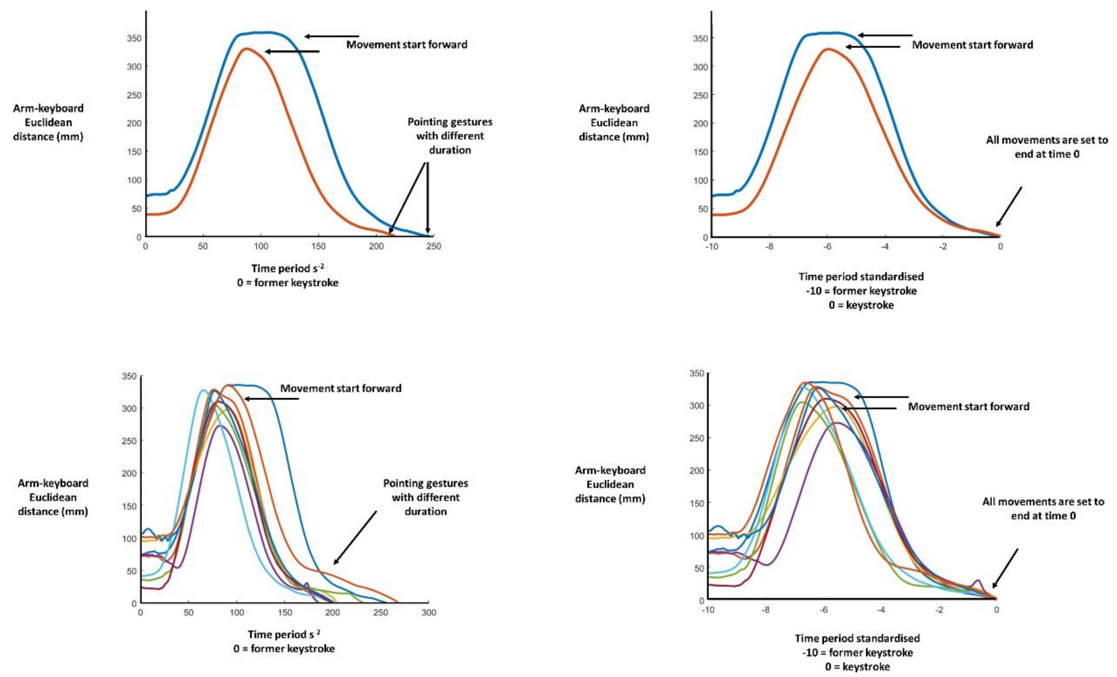

Fig.II.1 Euclidean distance movement profiles. The picture displays the movement profiles resulting from the calculation of the arm Euclidean distance from the endpoint target. In figure 3a and 3c, right side of the picture, the x-axis refers to a non-standardized temporal dimension. 0 values in the x-axis refers to the end of the previous pointing movement. In figure 3b and 3c, the x-axis refers to a standardized temporal dimension. The duration of each movement profile was standardized, assigning a value of -10 to the end of the former pointing and a value of 0 to the moment the user strokes the key. As a consequence, all the movement profile are inserted within an identical and *comparable time reference. The resulting movement profile delineates a returning phase (left side) and a pointing phase (right side) within the inter-keystroke interval. Differentiating return and forward gestures relied on identifying the highest y-axis value, signifying the major distance from the keyboard, as the start of the forward movement (see arrows "movement start forward").*

From the movement profile obtained through the Euclidean distance analysis, we could derive the speed profile of each pointing gesture. The speed profile was calculated as the first derivate of the movement profile. As it is possible to see from figure II.2, the speed profile has a sinusoidal shape. The backwards phase of the movement has negative velocity values, while the forward phase has positive values. The intersection of the speed profile with the x-axis represents the beginning of the forward phase of the movement, where the direction of velocity is inverted.

The speed profile here displayed also enables us to visualize the two components of the forward phase of the movement described by Meyer et al. (1988). Accordingly, a voluntary movement is composed of a ballistic and a closed loop phase. The ballistic phase is characterized by a rapid and largely pre-programmed motion. In this stage, the movement is initiated with a burst of activity, executing the initial part of the trajectory without relying on external feedback. It is often considered an open-loop process, as it doesn't involve continuous adjustment based on sensory information during its execution. On the other hand, the closed loop phase involves feedback mechanisms. It is a more controlled and adaptive part of the movement, where sensory input is continuously monitored and used to adjust and refine the ongoing action. This phase allows for corrections based on the environment or unexpected changes in the initial plan, enhancing precision and flexibility in executing the movement. Together, these two phases contribute to the overall efficiency and accuracy of voluntary movements, providing a comprehensive understanding of the intricate dynamics involved in motor control.

With a reference to the graph, if we only consider the positive values of the velocity profile, we could roughly divide the profile into two parts: a bell-shaped profile and an elongated tail. The bell-shaped profile that contains the velocity peak can be associated with the ballistic phase of the movement, while the elongated tail to the closed-loop phase of the gesture.

The information obtained through the calculation of speed profiles is used in the tortuosity index and eye-tracking analysis.

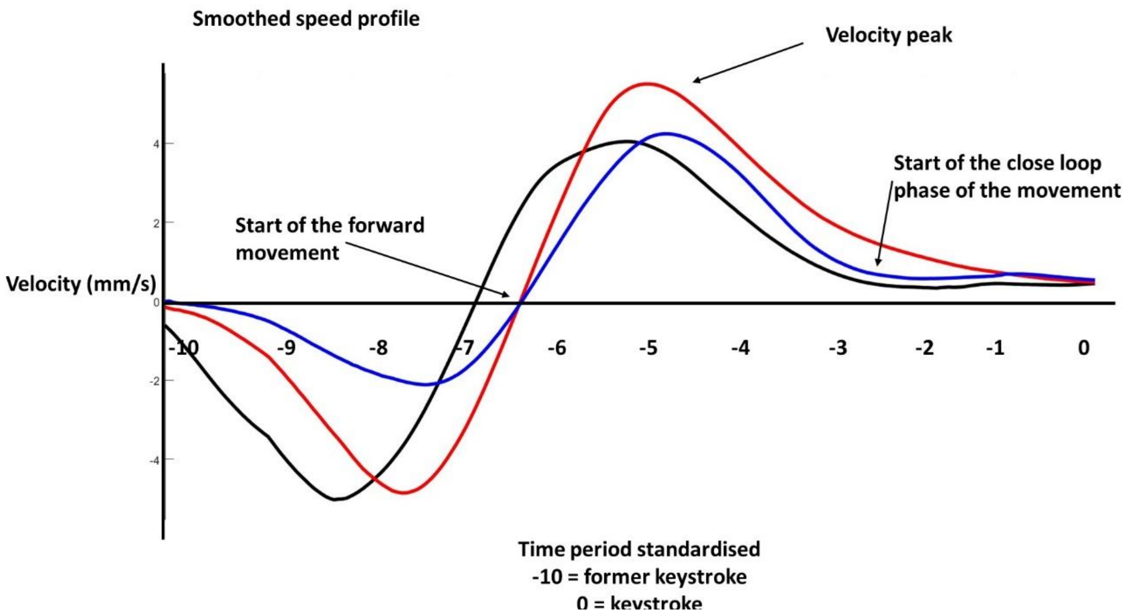

Fig. II.2 Speed profile of three consecutive movements. The picture displays the speed profile of three consecutive pointing gestures within a standardized time reference. Speed profile was calculated as the first derivate of the Euclidean distance profile. The x-axis reports the standardized timeframe. The y-axis reports the movement velocity. The displayed speed profiles have generally a sinusoidal shape. Negative speed values refer to the portion of the movement away from the keyboard, while positive velocity values refer to movement approaching the keyboard. The intersection of the speed profile with the x-axis (speed = 0) represents the start of the forward movement.

APPENDIX III – EYE TRACKING ANALYSIS

As shown by figure 1 in the main text, we could also synchronize to the movement profile the position of participants visual fixations and plot them in the same temporal framework.
The BeGaze software automatically detect and distinguish between visual intakes, saccades, and blinks. Given this automated analysis it was possible to manually assign each fixation (visual intake) to a specific place in the keyboard. For this purpose, we took as a reference the picture of the keyboard used during the data collection (please refers to figure 6 in S5 – Key to key distance computation). An 8x17 AOIs grid overlapped the keyboard's picture.

It should be noted that the number of AOIs exceed the number of keys available in the keyboard. This was due to the fact that some gaze data were badly calibrated. Thus, visual intakes while reflecting some movement over the keyboard did not match any key. For this reason, the keyboard grid was extended to 2 lines above and two lines below (see picture Y). We registered the position of fixation of the space outside in those cases where the data were badly calibrated. A separate grid was created for when users gazed at the text editor in the PC screen.

Once manually coded for each fixation its relative position on the keyboard, the data were exported into MATLAB.
The fixation data were synchronized with the pointing gesture by matching the eye-tracking video recordings to keystroke information. We used the timestamp of the first keystroke in the eye-tracking video as a reference point to align the two timeseries. Each visual fixation was then assigned a standardized time, indicating the proportion of the arm movement during which the eye fixation occurred. This scale ranged from 0, marking the start of the pointing movement, to 10, marking the moment the finger pressed the keyboard.

This way it was possible to extract information regarding:

- The beginning of the visual intake with respect to the arm position.
- The end of the visual intake with respect to the arm position.
- The position (with respect to the keyboard or the screen of the visual intake).

APPENDIX IV – MACHINE LEARNING ANALYSIS

The top part of figure 1 (in the main text), display a sequence of key labels that refers to the prediction of the endpoint target at the plotted time.

This set of data was the result of a machine learning algorithm trained on information gained from the key-logger and the motion system. The ML algorithm could evaluate the degree of predictability of each movement at different times and on the basis of the arm position. As we have seen, knowing where the pointing movement is aiming at is a crucial information in the context of FC. The chance of determining at what time the sole position of the arm can suggest the final direction of the pointing is central, as it can indirectly tell at what point the decision on which key to press is made. ML analysis was conducted within MATLAB classification learner toolbox with the Kernel Naïve Bayes method. At a single participant level, the algorithm predicts the expected endpoint target of every pointing gesture at each time, on the basis of a model trained with all the 3D coordinates extracted from each time.

Data processing

The duration of each pointing gesture was divided into 11 standardized time units. T = -10 indicates the end of the former movement. T = 0 indicates the end of movement (keystroke). Then, we extracted the 3D coordinates at each T. The result was a table for each participant where all the 3D coordinates at each single t were reported, see table below

	X-coordinate				**Y-coordinate**				**Z-coordinate**				**Class**
Movement	t-10	t-9	…	t 0	t-10	t-9	…	t 0	t-10	t-9	…	t 0	
1	x	x	x	x	y	y	y	y	z	z	z	z	"a"
2	x	x	x	x	y	y	y	y	z	z	z	z	"i"
3	x	x	x	x	y	y	y	y	z	z	z	x	"u"
4	x	x	x	x	y	y	y	y	z	z	z	z	"t"

Table IV.1 Example of data preparation for ML The table exemplifies how arm movements and typing timer data were arranged in preparation for the Machine Learning analysis. For each movement, we extracted the three-dimensional spatial coordinates (X-coordinate, Y-coordinate, Z-coordinate) at 11 standardized time units, with t-10 representing the end of the previous movement and t = 0 representing the exact time the user strikes the key. This resulted in nx34 table, with n equal to the number of pointing gesture performed by a single user. To the 33 coordinates values extracted for each pointing a column was added with the indication of the label of the key pressed.

Data training

A model was trained with all the 3D position data at each specific time units (see table IV.2), on a single participant level. The class for each position data was specified in the dataset to train the model in the definition of a trajectory path for each class (pressed key).

The training set works in defining for each class of object (keys) at each specific t a set of 3D spatial coordinates. For example, the training set determines that at t = -6, movements that ends on the “a” key usually occupy the coordinates comprised between x1-x5, y1-5, and z1-z5, while at t = -4 the same movement are positioned between x7-x8, y2-y3 and z8-z9. Clearly at t values distant from 0 the coordinates boundaries will be wider and less precise. Moreover, the more the pointing trajectory is erratic the less precise will be the trained model.

Data test

The position data for each single movement was then singularly tested against the whole model. The algorithm works by predicting the endpoint position of the movement (the target key) on the basis of the coordinates’ boundaries calculated by the training set. Thus, to the 3D position of the tested movement was assigned the class associated to its spatial coordinates. The test returned for each time unit the predicted class of the arm position, see table 11. We expect the model to have an increased accuracy as long as t values approach 0. At t = 0 the ML algorithm is able to accurately classify each 3D position to its real class (the pressed key). At t = -10 the ability of the algorithm to correctly classify the 3D position according to its class is at chance level.

Movement n°		**T-10**	**T-9**	**…**	**T 0**	**Actual Keystroke**
Mov 1	Predicted key	“F”	“Q”	…	“A”	“A”
Mov 2	Predicted key	“R”	“E”	…	“B”	“B”
Mov 3	Predicted key	“T”	“R”	…	“C”	“C”
Mov 4	Predicted key	“S”	“Y”	…	“D”	“D”

Table IV.2 Example of ML results. The table exemplifies the results of the Machine Learning analysis. For each movement the analysis reported the key-predicted at each time unit. For example, considering Mov 1, at T = -10 the algorithm predicts that the movement will end on the key “F”, at T = -9 it predicts that the pointing will end on the key “Q”, at T = 0 the algorithm correctly predicts that the pointing will end on the key “A”.

APPENDIX V – KEY TO KEY DISTANCE COMPUTATION

To further interpret and quantify the qualitative keys indication provided by the eye-tracking and machine learning analysis we computed the Euclidean distance between the predicted or fixated key and the target key. A 2D value was assigned to each predicted or fixated key: one referring to the X-dimension the other to the Y dimension as it is possible to see in table V.1. Then the Euclidean distance was calculated with the formula:

$$\text{square root } ((xQ-xA)\ \hat{}2 + (yQ-yA)\ \hat{}2)) \qquad (2)$$

The distance between the key "A" from the key "Q" would be computed as follow:

"A" x = -5, y = 0

"Q" x = -5 y = -1

Given the formula in (2):

square root ((-5 - -5) ^2+(-1-0) ^2)) = square root (1) = 1.

-3	**esc**	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**	**F10**	**F11**	**F12**	**B51**	**B52**	**B53**	**B54**	**B5**
-2	\	1	2	3	4	5	6	7	8	9	0	'	ì	Back space	B1	Ins	Arrow	Pag UP
-1	Tab	Q	W	E	R	T	Y	U	I	O	P	è	+	ù	B2	canc	fine	Pag Do
0	Caps Lock	A	S	D	F	G	H	J	K	L	ò	à	Enter 1	Enter 2	B3	B4	esc	B5
1	Shift	<	Z	X	C	V	B	N	M	;	:	-	Shift 1	Shift 2	B5	B6	Arrow up	B7
2	B8	B9	Ctrl	wind	Alt	Sp1	Sp2	Sp3	Sp4	Sp5	AltGr	B10	B11	B12	B13	Arrow left	B14	Arr Rig
3	B15	B16	B17	B18	B19	B20	B21	B22	B23	B24	B25	B26	B27	B28	B29	B30	B31	B3
4	B33	B34	B35	B36	B37	B38	B39	B40	B41	B42	B43	B44	B45	B46	B47	B48	B49	B5
y/x	**-6**	**-5**	**-4**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**

Table V.1: Keyboard representation and two-dimensional values associated to each key. The table represents the grid used for computing the Euclidean distance between keys. This calculation served the Machine Learning analysis and the eye-tracking analysis. The grid aims at reproducing an Italian laptop keyboard. Due to eye-tracking bad calibration the grid had to be expanded, particularly on the bottom part, by adding some extra keys. All the extra keys are coded with the letter "B" followed by a number. 55 extra keys were created to allow the AOIs coding during the eye-tracking data processing. To each key a 2D value (highlighted in blue and orange) was then assigned.

APPENDIX – VI DATA SUMMARY

Movement data from P2, P3, P5, P10 could not be considered in the analysis due to file corruption or excessive noise in the motion signal. Eye-tracking data from 5 participants (P1, P2, P3, P5, P10 and P12) were not accessible due to file corruption. As well, facilitators' eye-tracking data were not used in this analysis: due to file corruption no facilitators' eye-movement registration overlapped with the registrations of the user.

Table VI.1 below reports the number of pointing gestures available for the different analysis. Notably, the number of pointing gestures available for the analyses involving eye-tracking are significantly lower.

Participant	Movement profiles, Tortuosity Index, Inter keystrokes interval, ML	Eye-tracking analysis
P1	2279	-
P2	-	-
P3	-	-
P4	2720	691
P5	-	-
P6	3347	429
P7	2682	634
P8	2568	588
P9	4548	738
P10	-	-
P11	2996	639
P12	1828	-
P13	3359	550

Table VI.1. Summary of data analysed for each participant. The table summarises for each user the number of pointing gestures considered for the different analysis. Due to file corruption, the number of pointing gestures that could be considered for analyses involving eye-tracking were substantially lower.