Touch may reduce cognitive load during assisted typing by individuals with developmental disabilities

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Many techniques have attempted to provide physical support to ease the execution of a typing task by individuals with developmental disabilities (DD). These techniques have been controversial due to concerns that the support provider's touch can influence the typed content. The most common interpretation of assisted typing as an ideomotor phenomenon has been qualified recently by studies showing that users with DD make identifiable contributions to the process. This paper suggests a neurophysiological pathway by which touch could lower the cognitive load of seated typing by people with DD. The required sensorimotor processes (stabilizing posture and planning and executing manual reaching movements) and cognitive operations (generating and transcribing linguistic material) place concurrent demands on cognitive resources, particularly executive function (EF). A range of developmental disabilities are characterized by deficits in sensorimotor and EF capacity. As light touch has been shown to facilitate postural coordination, it is proposed that a facilitator's touch could assist the seated typist with sensorimotor and EF deficits by reducing their sensorimotor workload and thereby freeing up shared cognitive resources for the linguistic elements of the task. This is the first theoretical framework for understanding how a facilitator's touch may assist individuals with DD to contribute linguistic content during touch-assisted typing.

KEYWORDS

cognitive load, developmental disabilities, autism, touch, light touch, executive function, cognitive-motor interference, assisted typing

1. Introduction

There have been several attempts to find strategies to physically support people with developmental disabilities (DD) in the generation of written linguistic content. The proposed methods include assisted typing (Lilienfeld et al., 2014; Jaswal et al., 2020), the rapid prompting method (Lilienfeld et al., 2014; Tostanoski et al., 2014) and facilitated communication (Wehrenfennig et al., 2008; Schlosser et al., 2014). Supported typing techniques usually involve an external assistant providing physical support at the level of the hand, arm, or shoulder of the user to help them point at objects or type on a keyboard.

Such interventions are adopted to enhance communicative options in people with various DD. They are generally introduced to people with little or no verbal communication

skills, but the application of these interventions can persist even after the development of verbal communication. Although most general interest in the adoption of such techniques has focused on people with autism, assisted typing techniques have also been used in people with communication difficulties who have other DD, for example Down syndrome, Cerebral Palsy, and Fragile X.

These approaches are controversial (Mostert, 2001), however, as a range of studies have found that the user's output is in most cases strongly influenced by the facilitator (Mostert, 2001, 2010; Wehrenfennig et al., 2008; Saloviita et al., 2014; Schlosser et al., 2014). Burgess et al. (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). 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. Some authors have continued testing the authorship of written content through "message passing" tasks, showing that users largely fail to transmit information that the assistant does not have (Wehrenfennig et al., 2008; Saloviita et al., 2014). Others 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 (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 Scopesi (2001), Emerson (2010), and more recently by Nicoli et al., (2021, under review), showed that textual output from supported typing contains linguistic patterns associated with both the assistant and the user. These results suggest that the whole 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 paper.

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 2.1.1. "Mechanical base"). Postural control involves the integration of vestibular, somatosensory, and visual information, which in turn loads the executive function (EF) system (Section "2.1.3. Executive function load of sensorimotor coordination"). 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 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. EF deficits in DD" 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 "2.2. Generating written content") and planning the movement sequence required to type out that content also comes with its own EF load (Section "2.1.2. Motor planning" and Section "2.1.3. Executive function load of sensorimotor coordination"). 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 aging (Section "3. Cognitive-motor interaction"). 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. The utility of touch information in balance control"). 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 "5. Sensorimotor deficits in DD" and "6. EF deficits in DD," individuals with developmental disabilities (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

TABLE 1 Summary of the executive functions required during a typing task.

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, analyze, 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.

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. Task analysis," 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 "3. Cognitive-motor interaction," 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. The utility of touch information in balance control," we present the literature on the role that touch can play in aiding postural control, thereby reducing cognitive load. In Section "5. Sensorimotor deficits in DD," we establish the relationship between DD and sensorimotor deficits, and then, in Section "6. EF deficits in DD," we demonstrate how a range of DD limit EF capacity. In Section "7. General discussion—Sequences of events," we synthesize 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.

2. Task analysis

As typing is a complex task that involves both sensorimotor and cognitive components, in this section we analyze 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.

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 stabilizes 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.

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

center 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 toward 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 stabilizing 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 stabilizing 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-centered, 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.

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 centered 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, utilizing 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).

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 stabilizing 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'kiï 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. EF deficits in DD."

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.

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 organized

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 organized 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 realizes 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).

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. EF deficits in DD" 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 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 utilize much of their EF resources on idea generation, conceptual organization, 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). 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, 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).

3. Cognitive-motor interaction

Section "2. Task analysis" 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 summarizes 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 aging on balance and gait control. Aging 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 utilize 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 prioritize 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 center-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 behavioral performance indicators such as response time and accuracy, and, more recently, at the neurophysiological level using electrophysiology (Swerdloff and Hargrove, 2020; Reiser et al., 2021).

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; Stephenson et al., 2020; Swerdloff and Hargrove, 2020; Reiser et al., 2021). 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 stabilization 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 center 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, maximizing 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 stabilize 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 emphasizes the fact that postural control in everyday life is almost always organized to enable some supra-postural tasks rather than simply to maximize 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 recognized 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 try to communicate by typing text.

4. The utility of touch information in balance control

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) but 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 aging (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 aging (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). 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 and sequencing functions involved in typed communication. Section "4. The utility of touch information in balance control" 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, 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 toward 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 toward 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.

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 summarizes 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, 2013; 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, 2015) 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; 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. 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 seated balancing (Genthon and Rougier, 2006; 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, 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. EF deficits in DD"), 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 et al. (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.

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 "2. Task analysis") and Table 1, where we presented a list of EFs and their role in a typing task. Deficits in planning would limit the strategies available for organizing 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.

Executive function (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).

7. General discussion—Sequences of events

This paper 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-centered levels. Even if the coordinates of the target key are computed at a visual level (eye-centered), a body-centered coordinate system is necessary to compute the position of the arm linked to the torso. Also, the usability of an eye-centered 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 summarized 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 stabilization 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.

This paper'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 paper are developed from the position that assisted typing is a co-created process. 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 (1978) 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 (1984) 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 (1984) are important to how we understand assisted typing techniques. If touch only served to provide specific cuing, then the situation would correspond to Wertsch's (1984) 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.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

GN, SM, and GP wrote the first draft of the manuscript. GN, SM, GP, AG, and AE revised the manuscript and contributed to the conceptual planning of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

GN and GP, who participated in this study in the role of Nottingham Trent University's Ph.D students, are both members of Vi Comunico Che Penso, a charitable organization whose mission includes supporting the development of facilitated communication.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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