Understanding the Effects of Restraining Finger Coactivation in Mid-Air Typing: from a Neuromechanical Perspective

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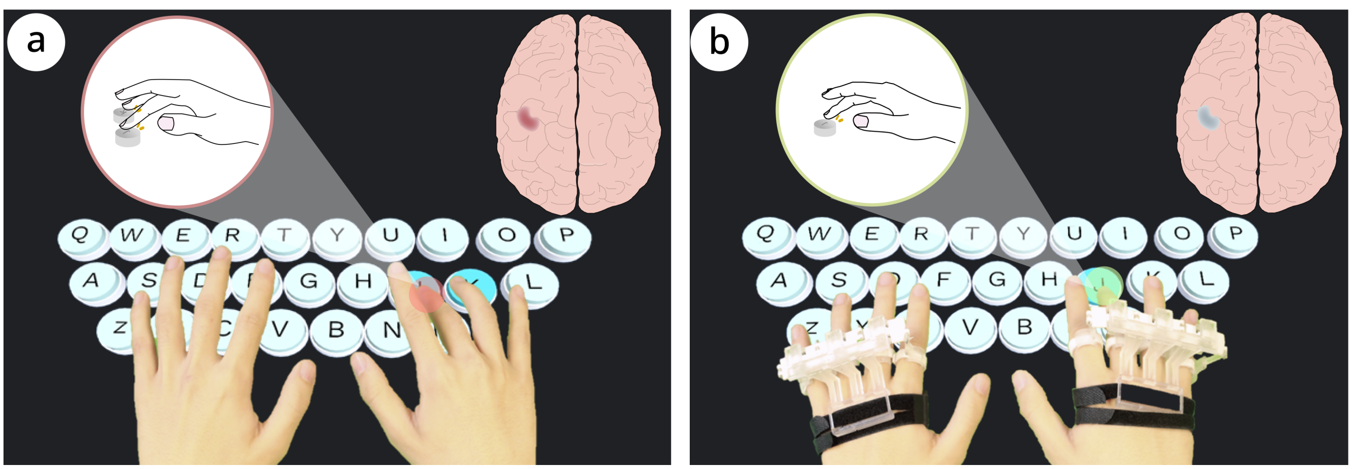

Figure 1: Restraining finger coactivation decreases errors and alleviates motor executive load during mid-air typing. a) Freehand mid-air typing; b) Mid-air typing with finger coactivation restrained.

ABSTRACT

Typing in mid-air is often perceived as intuitive yet presents challenges due to finger coactivation, a neuromechanical phenomenon that involves involuntary finger movements stemming from the lack of physical constraints. Previous studies were used to examine and address the impacts of finger coactivation using algorithmic approaches. Alternatively, this paper explores the neuromechanical effects of finger coactivation on mid-air typing, aiming to deepen

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our understanding and provide valuable insights to improve these interactions. We utilized a wearable device that restrains finger coactivation as a prop to conduct two mid-air studies, including a rapid finger-tapping task and a ten-finger typing task. The results revealed that restraining coactivation not only reduced mispresses, which is a classic coactivated error always considered as harm caused by coactivation. Unexpectedly, the reduction of motor control errors and spelling errors, thinking as non-coactivated errors, also be observed. Additionally, the study evaluated the neural resources involved in motor execution using functional Near Infrared Spectroscopy (fNIRS), which tracked cortical arousal during mid-air typing. The findings demonstrated decreased activation in the primary motor cortex of the left hemisphere when coactivation was restrained, suggesting a diminished motor execution load. This reduction suggests that a portion of neural resources is conserved, which also potentially aligns with perceived lower mental workload and decreased frustration levels.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**.

KEYWORDS

Mid-air typing, Finger coactivation, Motor constraint

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1 INTRODUCTION

Freehand mid-air typing has been of special importance to VR/AR interaction. However, it poses challenges due to the absence of haptic feedback and physical constraints, leading to larger finger movements, reduced efficiency, and discomfort such as temporary motor fatigue. Finger coactivation, caused by the neuromechanical nature of human finger movements, plays a significant role in affecting the performance of mid-air typing. Previous studies characterized the finger motions and developed algorithmic approaches to resolve the ambiguity and improve the performance of mid-air typing [17, 21, 68]. On the one hand, these methods do not intervene with users' intrinsic typing behaviors and require no hardware auxiliaries, but on the other hand, there remains a knowledge gap regarding how finger coactivation affects typing performance and leads to a negative user experience. Such knowledge could potentially guide the future development of novel intervening methods to mitigate finger coactivation problems and facilitate mid-air typing.

Finger coactivation is attributed to both mechanical and neural factors. Physiologically, it is due to the coupling between muscles or tendons across different fingers [37, 85], while neurologically, it arises from overlapping motor cortex areas for controlling individual fingers [61, 62]. Finger coactivation serves as a manifestation of hand coordination patterns, offering a means to streamline control over numerous degrees of freedom in hand joints or muscles. However, it also somewhat limits the ability to move fingers independently [38, 77], posing challenges for precise manipulations requiring the independent movement of fingers, especially in complex motor tasks. A physical keyboard for a PC or piano provides natural physical constraints, which prevent excessive and involuntary finger movements. In contrast, the absence of physical keyboards in mid-air typing takes away the physical constraints, hence, individuals start to consciously inhibit the coactivation to prevent incorrect inputs from unintended finger movements [26]. Finger coactivation becomes a hindrance to motor control in such scenarios.

In this work, We present a novel perspective on understanding finger coactivation in mid-air typing, focusing on its impact on motor performance and user experience. Our aim is to provide neuromechanical insights into how finger coactivation influences typing tasks. To achieve this, We devised an intervention method that restrains finger coactivation during mid-air typing tasks and used it as a prop to conduct two studies involving multi-finger movements under the conditions of both restraining and not restraining finger coactivation. Study 1 asked participants to bend their fingers repetitively in a given order as quickly as possible, which was referred to as a finger-tapping task. The findings indicated that restraining finger coactivation decreased the error rate of the two most error-prone sequences from 17.7% to 11.1% and from 23.3% to 13.4%, respectively. Mistakes were particularly reduced in movements involving the middle finger, which has the lowest independence. Unexpectedly, restraining finger coactivation not only eliminated mispresses but also reduced motor control errors, which refer to temporary loss of control of the fingers. This type of error has rarely been associated with coactivation in previous studies. However, the reduction in error rate did not extend to the left hand, as participants tended to move their non-dominant hand's fingers more slowly, naturally reducing the error rate due to lesser coactivation. These findings sparked our curiosity about how human neural resources are allocated during finger movements, leading us to conduct Study 2.

Study 2 was a mid-air typing task conducted within a VR environment utilizing a QWERTY virtual keyboard interface. Study 2 involved more intricate sequences comprising discrete motor actions rather than mere repetitive motions, thus increasing mental workload [34] in a manner more reflective of real-life multi-finger typing scenarios encountered in VR office settings. Consequently, we employed Functional Near-Infrared Spectroscopy (fNIRS) to evaluate the neural resources involved in motor control, particularly the motor executive load, to better understand the mental workload and its impact on user experience [43]. The findings demonstrate that restraining finger coactivation enhances input performance by reducing both coactivated errors and spelling errors (non-coactivated errors) without compromising typing speed. Different from Study 1, here the spelling errors are prominent because Study 2 did not ask intensively for motor control but high cognitive function of planning the order of keystrokes in text typing. Also, the reduction of errors extends the applicability to both hands due to the consistent typing speed of two hands. Furthermore, analysis of cortical arousal reveals a diminished motor execution load is observed in the Primary Motor Cortex of the left hemisphere. The conservation of neural resources required for motor control and cognitive functions may also correspond to reduced mental demand and frustration, as indicated by subjective reports from the NASA-TLX questionnaire.

This paper enhances our understanding of how restraining finger coactivation affects mid-air typing by comparing performance and motor executive load between conditions of restrained and unrestrained finger coactivation. Our contributions are: 1) through empirical and psychophysical research, we found that restraining finger coactivation reduces not only mispresses (coactivated errors) but also motor control errors in sequential tapping and spelling errors in typing; 2) elucidating the mechanisms by which coactivation induced motor executive load and diminished typing efficiency lead to a suboptimal user experience in mid-air typing; 3) offering insights for advancing mid-air typing in spatial interactions, with an emphasis on including moderate motor constraints.

2 RELATED WORK

Our study investigates the impact of finger coactivation on mid-air typing, aiming to enhance understanding of its neuromechanical effects. This research is closely aligned with previous studies on mid-air typing interfaces, neuromechanical investigations into finger coactivation, and the mechanisms underlying motor control.

2.1 Mid-air Typing

Spatial interaction has gained prominence, with numerous mid-air input strategies proposed in virtual reality (VR) [35]. Users commonly interact with virtual objects using hand-eye coordination, and freehand mid-air input tracked by sensors is deemed the most intuitive approach [64, 71]. As a typical input scenario in VR, mid-air typing has evolved from traditional ten-finger typing methods. However, a major challenge hindering the widespread use of mid-air typing is accurately classifying keystrokes, necessitating complex algorithms to infer user input from continuous finger movement data. This has led to research focused on optimizing algorithms for precise detection of voluntary finger movements, especially when multiple fingers move simultaneously [17, 21, 68, 89].

To enhance the adaptability of finger motion capture algorithms, some researchers utilize Inertial Measurement Unit (IMU) sensors to collect gesture information. Streli et al. [69] employs inertial sensors to enable full-size typing on passive surfaces, achieving an average input speed of 19 Words Per Minute (WPM). Similar devices [23, 24, 42, 94], detect touch events and predict users' desired word based on the orientation of the IMU ring. Utilizing wearable motion and inductive sensors to detect finger taps typically requires a physical plane to provide tactile cues to users, thereby reducing tapping fatigue.

An alternative approach involves integrating actuators onto the fingertips to provide haptic feedback during virtual keystrokes, as seen in devices such as Haptag [7], MagnetIO [47], Touch&Fold [74], contactless devices [25, 59] and wearables [56, 70, 74]. Another approach involves departing from traditional QWERTY keyboard layouts and using two fingers, as demonstrated in systems such as PinchType [13], HiFinger [31], PizzaText [90], and FingerText [39]. These systems rely on two-finger contact to provide tactile sensation and serve as input. While these studies collect extensive finger movement data and establish corresponding algorithm models, the primary challenge with these two finger typing systems is the steep learning curve, requiring significant user training before effective usage.

Typing on physical surfaces or pitch on two fingers not only offers essential haptic cues on fingertips, a well-studied aspect that imposes natural physical constraints that deter excessive finger movements. Moreover, the physical contact between the fingers and the keyboard enhances finger independence, akin to releasing a single finger from an object during multi-finger grasping. This coordinated relationship between fingers and keys, established by placing hands on the keyboard, improves the motor coordinating abilities of the fingers [15, 62].

Despite the variety of methods employed to facilitate mid-air typing, there remains a lack of understanding regarding how finger coactivation impacts typing efficiency and user experiences. Our work addresses this gap by investigating the benefits of restraining finger coactivation from a neuromechanical perspective.

2.2 Finger Coactivation

Finger coactivation, defined as the unconscious generation of force or displacement by other fingers when a specific finger is directed for voluntary force application or displacement generation [60, 93], reduces individual finger motor independence. Termed "finger interdependency" [22, 55] or "finger enslaving" [10], this phenomenon has been extensively studied in the fields of neurophysiology, sports biomechanics, and human kinetics.

Previous research on finger force coactivation has primarily focused on non-autonomous forces during maximal autonomic force production and force coordination [46, 92]. Such studies have highlighted that coactivation effects are more pronounced on adjacent fingers, with the index finger exhibiting relatively high independence (excluding the thumb), while the ring finger generally displays the least independence. Moreover, force coactivation tends to be nearly symmetrical [26, 43, 92, 93]. In contrast to static force coactivation, motor coactivation reflects more mechanical coupling between fingers, involving coactivation between individual fingers [26]. Similarly, the index finger typically demonstrates greater independence, albeit with a degree of interdependence during less extensive finger movement [80]. Notably, the movement of a single finger entails cooperation among three finger joints, leading to studies on isolated single-joint coactivation. For instance, Li et al. [41] investigated motor coactivation during isolated flexion of the distal interphalangeal joint, revealing less independence compared to movements involving the entire finger.

Research has also explored coactivation in advanced motor skills such as piano playing or typing. Pianists often exhibit highly individualized finger movements, maintaining consistent finger independence even at faster tempos, unlike the general population, where finger coactivation intensifies with increased speed [18, 20]. Nonetheless, individuals can improve finger independence through piano exercises or isolated finger movement exercises, attributed to neuroplastic adaptation [19, 29, 32, 65].

In contrast, mid-air typing lacks the physical constraints inherent in traditional typing, thereby posing challenges to user performance and experiences related to finger coactivation. Specifically, while it is inferred, but not conclusively verified, that unintentional coactivation of adjacent fingers hampers users' motor ability to execute sequential typing actions, this phenomenon manifests not only at the muscular level but also at the neural level governing motor control.

2.3 Finger Motor Control

The concept of motor control, encompassing the initiation, direction, and modulation of voluntary movement [50], relies on intricate communication between the Central Nervous System (CNS) and Peripheral Nervous System (PNS) [79]. Studies have highlighted the involvement of the primary motor cortex, pre-motor cortex, and supplementary motor area (SMA) in regulating finger movements.

Further exploration in motor control delves into the neurological constraints influencing independent finger control [45]. Spatially overlapping motor neurons dictate a sequential activation pattern, evidenced by short-term synchronization between motor units, strongest among adjacent fingers and diminishing with distance, particularly prominent during extension over flexion [48]. This synchronization pattern provides a neural basis for finger coactivation [91], as the CNS modulates finger joint degrees of freedom to optimize posture [76, 81]. In summary, coactivation arises from the overlapping control of individual fingers by the motor cortex [61, 62].

Tactile and proprioceptive feedback play crucial roles in closed-loop control mechanisms [83]. The significance of tactile feedback in finger keypress movements has been thoroughly examined, where the ability of users' fingers to consistently reach target positions impacts the subsequent motion sequences. While haptic cues are vital feedback in mid-air interaction for indicating finger starting positions and confirming contact, they do not directly influence motor execution [58]. In contrast, motor coactivation significantly affects the sequencing of finger flexing [11, 14, 43, 44, 66, 84].

Drawing upon the insights mentioned above, we are interested in looking into the impact of finger coactivation via having it restrained and investigating the behavioral and neurological benefits of such motor constraints in mid-air typing.

3 A MECHANICAL DEVICE FOR RESTRAINING FINGER COACTIVATION

To execute the investigations, we first built a wearable kinematic device to restrain the finger's unintentional motions, a straightforward yet efficient way to intervene in the coactivation. We used it as a prop for the following studies.

3.1 Apparatus

In the pursuit of technologies aimed at enhancing or constraining finger motor abilities, researchers have devised various exoskeleton devices. Many of these wearables employ diverse braking mechanisms to regulate finger movement, categorizable into two primary actuation methods. The first method relies on kinematic force feedback combined with real-time motion sensors to modulate the torque of mechanical exoskeletons through the use of active electromechanical, pneumatic, and electrostatic actuators [5, 9, 36, 75]. This approach aims to achieve precise control over finger movements by dynamically adjusting resistance based on sensor data. The second method utilizes passive mechanical clutches that engage in response to finger movements [4, 6, 49, 51, 52, 57], offering a simpler and potentially more reliable solution by avoiding the complexities and potential delays [86] associated with active control systems. Therefore, this work introduces a passive braking mechanism based on finger interlocking to create the prop used in the studies. The apparatus avoids using electrical components and complex algorithms for sensing active fingers, allowing it to accommodate varying typing habits.

The interlocking mechanism, illustrated in Figure 2, features two independent ratchets positioned around a centrally located bidirectional ratchet paw. When one ratchet rotates, it unbalances the ratchet paw, causing it to engage with the groove of the opposing ratchet, thereby inhibiting its movement. The ratchets and ratchet paws are fixed by shafts, with a distance of 7mm between each one. To enable ratchet resetting and connection with wearable components, each ratchet is attached to a hinge and linked to the finger via the connecting rod. When the finger bends, it exerts a downward force on the ratchet, causing it to rotate and lock the adjacent ratchets, thereby preventing unintentional movement of the neighboring fingers. A torsion spring located beneath the hinge facilitates the ratchets' return to their starting positions following the completion of this action.

In evaluating the coactivation intervention apparatus's mechanical properties, we analyzed its design and overall construction. The device integrates high-precision stainless steel for the shaft and torsion spring, while its remaining parts are fabricated using 3D printing technology. With a total mass of 19.60 grams, the apparatus is mounted on the proximal phalanx, influencing mainly the metacarpophalangeal joint (MCP). This strategic placement ensures the preservation of the finger's bending capability while accommodating slight lateral or medial rotations, thereby allowing adjustments to the fingertip's positioning. The study excluded the thumb due to its inherent dexterity. Next, we conducted a test to assess whether the device could withstand the force of finger coactivation. Six participants (3 females, aged 22 to 26) placed their fingers on a pressure sensor one at a time, and we measured the pressure change when an adjacent finger was bent. Results showed that involuntary finger movements generated a maximum force of 2.7N, averaging of 1.5N (SD = 0.47N). The device applies an average braking force of 7.13N (SD = 0.06N) on adjacent fingers measured by a dynamometer, confirming the apparatus's ability to be used as a prop for subsequent experiments.

3.2 Quantitative Experiment

A quantitative experiment was designed to examine the effectiveness of the coactivation intervention apparatus by comparing the independent index of finger coactivation between freehand and wearing apparatus. Six healthy right-handed participants, aged between 25 and 28 years (4 females), with no history of upper extremity neuropathy or trauma, were recruited for the study. All of the participants had yet to gain experience with hand instruments.

The participants were instructed to flex a specified finger to its maximum MCP angle. While not resisting the involuntary movement in the non-specified finger. This trial was repeated 5 times for

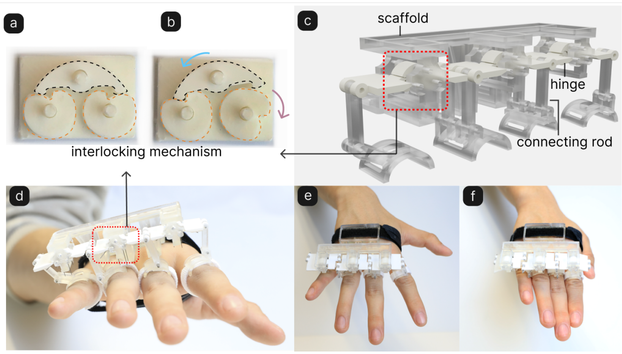

Figure 2: Principle of braking mechanical structure (a) The initial state of the braking mechanism. (b) The rotation of the right ratchet of the braking mechanism drives the pawl to rotate counterclockwise, thereby locking the left ratchet. (c) The assembly diagram of the apparatus. (d) The user wears the apparatus. (e) The user wears the device with five fingers spread out. (f) The user wears the device with five fingers together.

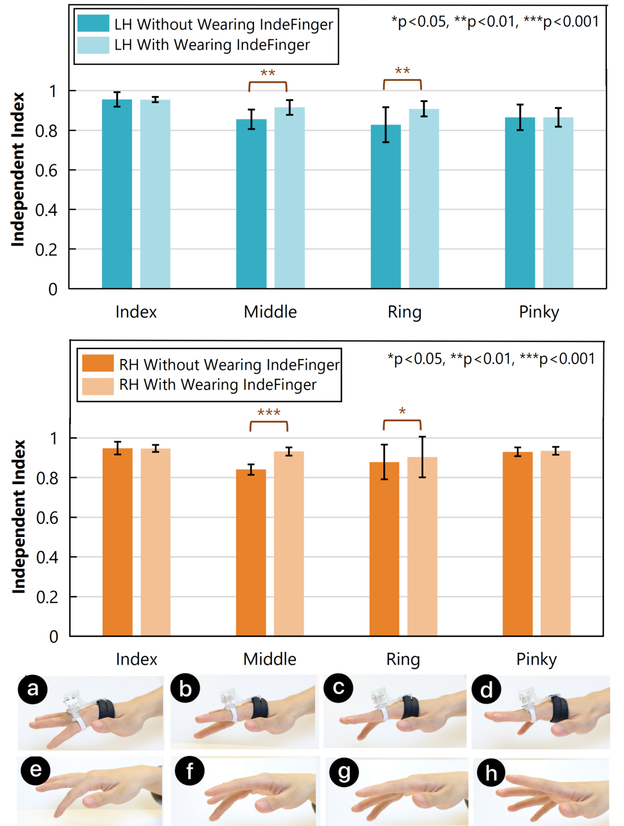

Figure 3: Coactivation intervention apparatus increases the independence of different fingers. Above: The effect of the apparatus on the finger independence of the Left Hand and Right Hand. Below: (a)-(d) show the performance of voluntary downward movement of a single finger while wearing the apparatus, (e)-(h) show the performance of voluntary downward movement of an individual finger when freehand.

each finger, totaling 20 trials, with a randomized order. The experiment, lasting about 5 minutes, was conducted with and without wearing apparatus. The data of finger joint angle was captured by Qualisys (Arqus A5) motion capture system. We quantified each finger's movement using the sum of metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joint angles. We calculated the Independent Finger Index (INDE) to assess the participants' ability to perform individual finger movements without causing unintentional movement in adjacent fingers [26]. Illustrated Figure 3, a value of 1 indicates perfect independence and a value of 0 indicates complete dependence. Using paired t-test, the INDE values of the LH-Middle finger ($p < 0.001$), the LH-Ring finger ($p < 0.001$), and the RH-Middle finger ($p < 0.001$) are significantly higher when wearing the apparatus compared to not wearing it. Other data do not conform to a normal distribution, so the Wilkson rank test is used. The INDE of the R-Ring ($p = 0.014$) is significantly improved, while the LH- &RH- Index fingers and LH-&RH-Pinky fingers have no significant difference between wearing the apparatus and not. This may be because they have a high degree of independence [26], which is associated with less co-activated movement. These results demonstrate that the coactivation intervention apparatus can significantly restrain the coactivation of fingers which has lower independence. To avoid the different wearable configurations drawing attention to certain fingers, we kept the braking mechanism for all fingers in subsequent studies.

4 STUDY 1: CYCLIC FINGER TAPPING TASK

Tapping tasks require fingers to bend rapidly and sequentially. Compared with a physical keyboard or surface, tapping in mid-air is accompanied by fierce finger coactivation, which causes incorrect inputs inadvertently. In this study, we designed a tapping task that executes simple cyclic actions in given orders in mid-air to examine whether restraining finger coactivation can improve users' ability to coordinate multi-fingers.

4.1 Background

The finger-tapping task, a foundational and prevalent method, facilitates the examination of finger motor characteristics and performance during the execution of simple sequences [2, 3]. Unlike the more complex movements involved in typing, this task employs rapid, cyclical motions that predominantly engage automatic motor control systems, relying on motor circuits rather than cognitive processes [40]. In this task, rapid finger movements are more prone to inducing coactivation, leading to mispresses. Additionally, such swift movements may result in temporary loss of motor control, causing errors. Consequently, it effectively isolates and assesses the motor capabilities of the fingers in performing sequential actions and elucidates the impact of restraining finger coactivation.

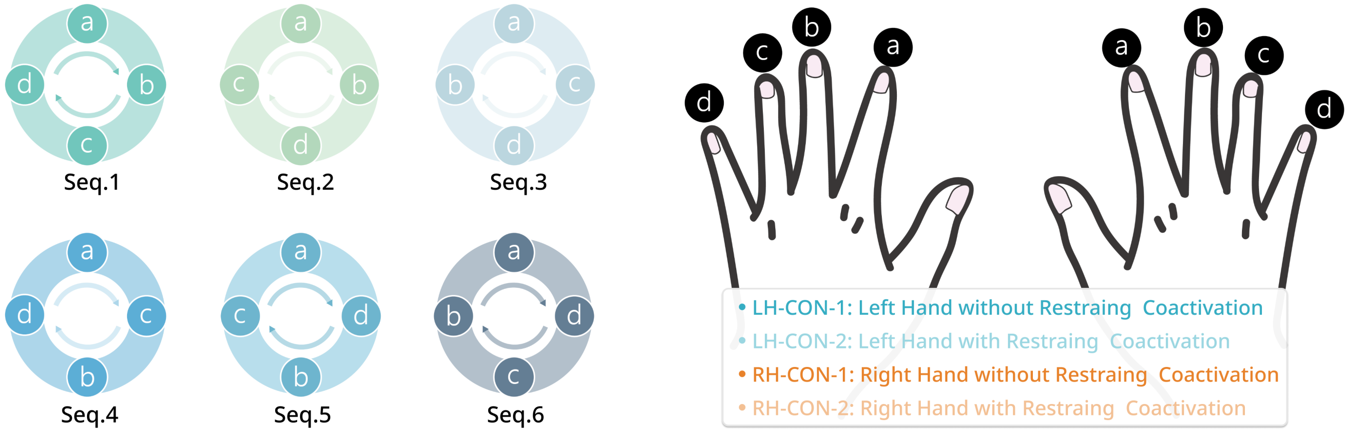

Figure 4: Left: Six defined sequences, each representing complete pairs of fingers, denoted by alphabetic indices. Right: Four distinct conditions within the tapping task are outlined. Abbreviations used in subsequent studies represent specific fingers and hands: 'a' for the index finger, 'b' for the middle finger, 'c' for the ring finger, 'd' for the pinky finger, 'LH' for the left hand, and 'RH' for the right hand. 'CON-1' indicates finger coactivation is not restrained and 'CON-2' indicates finger coactivation is restrained.

4.2 Study Design

This study aimed to investigate the impact of restraining finger coactivation on the performance of a multi-finger rapid sequential tapping task. Six distinct sequences (Seq.) were established to encompass all possible configurations for alternating four-finger tapping orders, as illustrated in Figure 4. The thumb was excluded due to its high independence. Adopting a within-subject design, the study manipulates several independent variables: the hand used (left/right), and the condition of with or without restraining finger coactivation, resulting in four distinct blocks, as shown in Figure 4. Within each block, participants executed six motor sequences involving all finger pairs. This design allowed for the observation of both mispresses and motor control errors. Each Seq. was randomly presented three times, resulting in a total of 18 trials.

4.3 Method

4.3.1 Participants. Sixteen (8 females; age M = 24.81 years and SD = 2.01 years) right-handed participants took part in this study, and each participant received a compensation of $5 for their time. Most of the participants did not have VR experience. All experimental procedures were approved by a local Ethics committee. Individuals suffering from abnormal sensory function in both hands or other hand diseases were excluded from the study.

4.3.2 Measures. The experiment took place within a virtual reality (VR) environment, developed using Unity software, and presented via a Quest 2 headset. During each trial, the participants interacted with the virtual scene by performing mid-air keystrokes, which were detected through the collision of virtual keys with their fingertips. The positions of the fingertips were accurately tracked using an OptiTrack motion capture system, with each keystroke meticulously logged as an input event.

To analyze sequential finger actions, paired finger combinations were extracted from input events. These combinations encompassed all possible finger pairings, spanning from radial to ulnar directions and vice versa, and encompassed both adjacent and non-adjacent finger pairs. For each Seq., only four specific paired finger combinations were designated as compliant and thus considered correct. Any other pairings were classified as erroneous paired fingers. To quantify the participants' performance, we introduced the following metrics:

- **Speed:** Defined as the ratio of the total count of input events to the time required to complete the task in each trial, expressed in characters per minute (CPM).
- **Error rate:** Calculated as the proportion of erroneous paired fingers relative to the total number of input events.
- **Error rate of specifically paired fingers:** Quantifies the proportion of errors associated with a specific pair of fingers during each trial.

4.3.3 Procedure. At first, the participants were provided with information about the study and gave informed consent. Participants then used a Quest Controller to set the virtual keys' distance according to their daily typing habits, ensuring efficient input. The infrared light of the controller did not interfere with the OptiTrack system, as the controller was not used during the formal experiment. In the training stage, the participants were given 12 minutes to acquaint themselves with the tasks and the apparatus, facilitating approximately 30 seconds of practice per Seq. for each hand both with and without the apparatus. The experimental phase employed four counterbalanced blocks across the conditions, each interspersed with a 3-minute rest period. In every block, participants were shown visual cues depicting a target Seq., followed by instructions to replicate the Seq. accurately and rapidly by tapping the corresponding virtual buttons with the designated fingers. Each trial was structured to include 15 seconds of activity and 8 seconds of rest, culminating in an overall duration of approximately 50 minutes per participant.

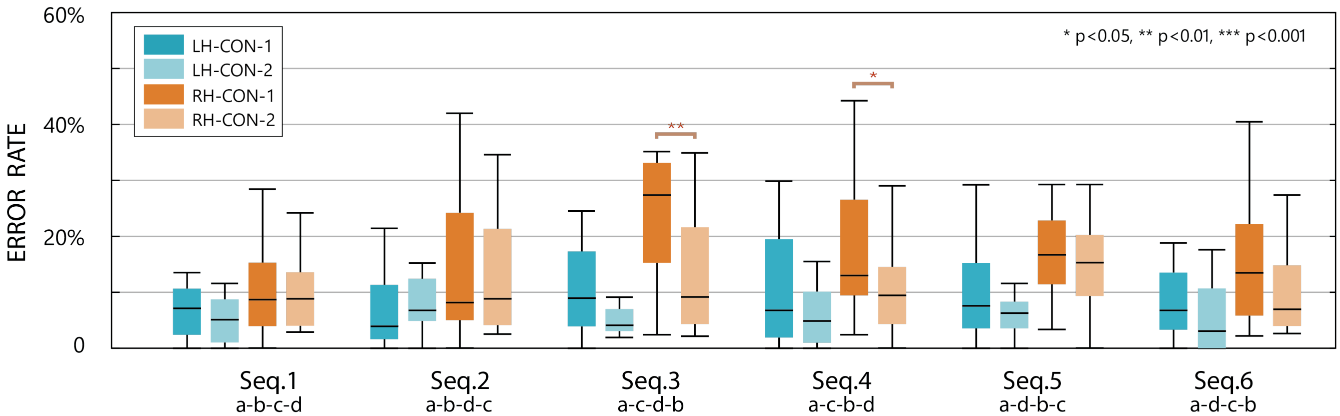

Figure 5: Error Rates Across Six Different Sequences (Seq.) by Hand (Left/Right) With and Without Restraining Finger Coactivation Conditions.

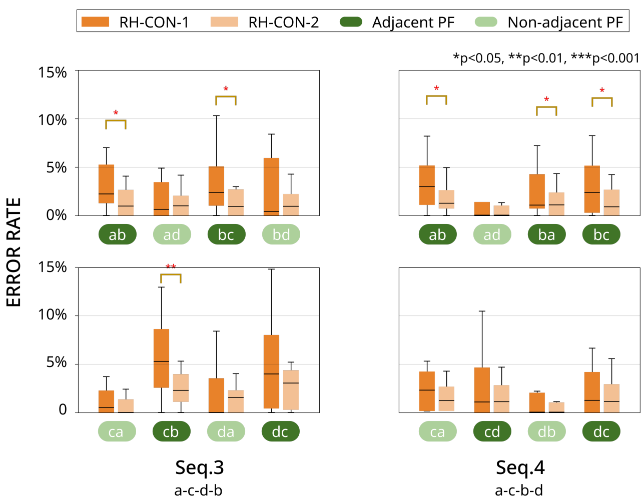

Figure 6: Error Rate for Paired Fingers in Seq.3 and Seq.4.

4.4 Results

4.4.1 Speed. We assessed **speed** differences between left and right hands with and without restraining finger coactivation for the 6 sequences. Repeated measures ANOVA revealed the three-way factor HAND∗Seq.∗CON has no interaction effect on **speed**, and the factor CON has no significant simple effect. On the whole, the mean speed of the right hand in CON-1 is 153 CPM (SD = 47.7 CPM); in CON-2, it is 141 CPM (SD = 29.9 CPM). The mean speed of the left hand is 135 CPM (SD = 31.8 CPM) in CON-1 and 125 CPM (SD = 33.7 CPM) in CON-2. The paired t-test also showed that restraining finger coactivation had no impact on speed across all 6 sequences, except a deceleration when the left hand executed Seq.4 (LH-CON-1[Mean ± SD = 135.8 ± 32.1], LH-CON-2[Mean ± SD = 118.5 ± 29.5], t = 3.241, p = 0.005). The repeated measures ANOVA also showed a significant effect of Seq. on speed (F(5, 75) = 11.5, p < 0.001, η^2 = 0.434). The Bonferroni-adjusted pairwise comparisons indicated that executing Seq.1 was significantly faster than executing Seq.2 (p = 0.001), Seq.3 (p < 0.001), and Seq.4 (p = 0.002). The factor HAND also has a significant effect on speed (F(1,15) = 18.241, p = 0.001, η^2 = 0.549), which indicates that the motor speed of the fingers of the left hand (Mean ± SD = 130.1 ± 33.1) is slower than the right hand (Mean ± SD = 147.6 ± 40.1).

4.4.2 Error rate. The analysis method is similar to the above. Because the data of LH-CON-1 and LH-CON-2 have a significant deviation from normal distribution, the repeated measures ANOVA is only used to examine the error rate of the right hand. The two-way factor CON∗Seq. has no significant effect on the error rate. The factor CON showed a significant effect (df = (1, 15), F = 7.655, p = 0.014, η^2 = 0.338). As shown in Figure 5, the paired t-test was utilized to compare **error rate** between two conditions. Significant differences were found in Seq.3 (a-c-d-b) for RH-CON-1 (Mean ± SD = 23.3% ± 10.8%) compared to RH-CON-2 (Mean ± SD = 13.4% ± 9.9%, t = 3.841, p = 0.002), as well as in Seq.4 (RH-CON-1 [Mean ± SD = 17.7% ± 11.7%], RH-CON-2[Mean ± SD = 11.1% ± 9.1%], t = 2.806, p = 0.013). These findings indicate that by restraining finger coactivation, the **error rate** of the right hand decreases.

The simple effect of factor Seq. is significant (df = (5, 75), F = 3.573, p = 0.006, η^2 = 0.192). Illustrated in Figure 5, Seq.3 exhibited the highest error rate, under RH-CON-1 condition, at 23%, closely followed by Seq.4 at 18%. In the freehand case, executing Seq.3 is significantly more error-prone than executing Seq.1 (p = 0.002), as revealed by Bonferroni-adjusted pairwise comparisons. When restraining finger coactivation, the difference is disappeared. For the error rate of the left hand, no significant difference was found compared restraining finger coactivation to not restraining by the Wilcoxon signed-rank test. Another finding is that the error rate of the left hand is lower than the right hand, occurring in Seq.3 (LH-CON-1[Mdn = 8.9%], RH-CON-1[Mdn = 27.2%], Z = -2.896, p = 0.004), Seq.4 (LH-CON-1[Mdn = 8.9%], RH-CON-1[Mdn = 12.8%], Z = -2.12, p = 0.034), and Seq.5 (LH-CON-1[Mdn = 7.7%], RH-CON-1[Mdn = 16.7%], Z = -2.43, p = 0.015).

4.4.3 Error rate of specific paired fingers. To identify the specific improvement in erroneous paired fingers contributing to the decrease in **error rate**, we focused on RH-CON-1 and RH-CON-2. In two sequences with significant **error rate** changes, we employed the Wilcoxon signed-rank test on the error rate of corresponding paired fingers across conditions (as shown in Figure 6). Notably, 4 paired fingers exhibited significant differences—three adjacent paired fingers (ab, ba, cb, bc). Following the use of coactivation intervention apparatus, the error rate of ab and bc appeared significantly lower in Seq.3 (ab[RH-CON-1: Mdn = 2.12%, RH-CON-2: Mdn = 0.99%, Z = -2.215, p = 0.027], bc[RH-CON-1: Mdn = 2.33%, RH-CON-2: Mdn = 0.92%, Z = -2.417, p = 0.016]) and Seq.4 (ab[RH-CON-1: Mdn = 2.98%, RH-CON-2: Mdn = 1.21%, Z = -2.068, p = 0.039], bc[RH-CON-1: Mdn = 2.43%, RH-CON-2: Mdn = 0.79%, Z = -1.988, p = 0.047]), respectively. Moreover, the frequency of cb (RH-CON-1: Mdn = 5.35%, RH-CON-2: Mdn = 2.27%, Z = -2.327, p = 0.02) significantly decreased in Seq.3. And the frequency of ba (RH-CON-1: Mdn = 1.06%, RH-CON-2: Mdn = 0.99%, Z = -2.062, p = 0.039) significantly decreased in Seq.4.

4.5 Experiment Discussion

When comparing speed differences with and without restraining finger coactivation, there was no significant reduction in speed observed in the right hand. In contrast, the left hand showed a speed reduction, but only in Seq.4. Thus, restraining finger coactivation had no impact on voluntary finger movement. The results regarding the error rate demonstrated that restraining finger coactivation enhances the accuracy of cyclic actions, especially in improving error-prone sequential movements. Specifically, imposing finger coactivation restraining resulted in a significant decrease in error rates for Seq.3 and Seq.4 in the right hand. Given that involuntary coactivated movement is more common during rapid and unintended motor actions [26], the left hand executed sequences more slowly than the right hand, potentially explaining why restraining finger coactivation did not yield results in the left hand. Besides, the left hand carries out sequential movements more precisely than the right hand, especially in sequences known to be error-prone such as Seq.3-5, where coordination challenges are typically more pronounced. One potential explanation for this discrepancy is that subjects tended to handle the fingers of the non-dominant hand more slowly and avoided coactivation.

Notably, significant reductions were observed only in the paired combination of the middle finger and its adjacent fingers, suggesting that restraining coactivation aids in enhancing cyclic motor accuracy by suppressing involuntary actions involving these finger combinations, both in the radial to ulnar and vice versa directions.

We infer that the observed improvement is attributed to the elimination of both mispresses and motor control errors involving the middle finger. Notably, the 'ab' error significantly decreased when finger coactivation was restrained. This error, where the middle finger mistakenly follows the index finger, is a motor control error, not a mispress, since the index finger is highly independent. These motor control errors likely arise from distractions while executing motor sequences, as participants allocate neural resources to suppress coactivated fingers. The 'dc' error follows a similar pattern, also resulting from motor control loss. In contrast, in the quantitative experiment in Section 3.2, participants moved their fingers more slowly while evaluating the device than in Study 1, potentially leading to fewer motor control errors. However, differentiating between mispresses (coactivated) and motor control (non-coactivated) errors remains challenging, exemplified by the uncertainty surrounding the 'bc' error.

Consequently, we conducted Study 2, which involved a multi-finger typing task requiring coordination of both hands, resulting in nearly identical speeds for both hands. Additionally, Study 2 utilized fNIRS to examine the motor executive load, aiding in the analysis of non-coactivated errors.

5 STUDY 2: MID-AIR TYPING TASK

Ten-finger typing is recognized as an efficient input method, yet its application in VR poses challenges due to inadvertent coactivation, resulting in reduced effectiveness and a negative user experience. This study involves a mid-air typing task conducted in a VR environment, with concurrent monitoring of cortical activation, to investigate the impact of restraining finger coactivation on typing performance and motor executive load.

5.1 Background

Finger behavior during mid-air typing, characterized by discrete motor acts rather than mere cyclic movements as observed in Study 1, engages a broader range of motor cortices. This distinction is crucial, as the automated motor control system may struggle to process such intricate tasks [34]. Consequently, monitoring the activity of cortical regions with diverse functions becomes imperative for analyzing the motor execution load during the task. To facilitate this analysis, we employed Functional Near-Infrared Spectroscopy (fNIRS) because of its non-invasive nature in measuring brain activity. This method has been proven effective in monitoring the degree of oxyhemoglobin saturation, a feature indicative of cortical neuron activation [67, 87]. In this study, fNIRS serves as a valuable tool for assessing the motor executive load during mid-air typing.

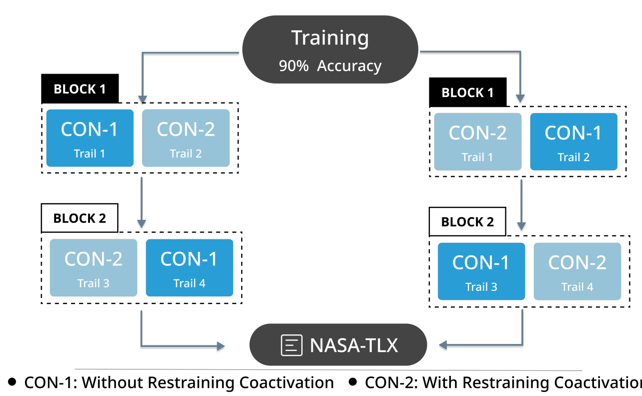

Figure 7: Overview of the Design and Procedure employed in Study 2.

5.2 Study Design

This study investigates mid-air typing in virtual reality using a virtual QWERTY keyboard. As shown in Figure 7, participants must complete a 150-character practice task within 120 seconds with at least 90% accuracy to proceed to the formal experiment. The practice task aims to ensure participants' familiarity with typing scenarios, as an error rate exceeding 10% is considered unreasonable [12]. In the formal task, participants are directed to type a 280-character essay, as depicted in Figure 8. Each trial requires participants to type with all ten fingers and finish the essay within 180 seconds to mitigate arm fatigue resulting from prolonged suspension in mid-air. The study's condition is whether restraining finger coactivation, which serves as a within-subject variable. To counterbalance, each participant's task is divided into two blocks, with the order of conditions reversed within each block. Although the text materials differ between the two blocks, they are consistent across two trials within one block, ensuring an equal frequency of finger use. All texts used consist of common words, with manual proofreading being equally challenging. Special characters and spaces are intentionally omitted from the essays to eliminate error correction time as a confounding factor [12].

Figure 8: Settings of the study 2. The participant is engaged in air typing while wearing functional near-infrared spectroscopy (fNIRS) devices.

5.3 Method

5.3.1 Participants. We recruited 12 participants (8 females), whose ages ranged from 22 to 28 (Mean ± SD = 24 ± 1.41). All the participants were not required to have VR experience, but all must be familiar with typing. Each participant received approximately $10 as compensation for their time.

5.3.2 Measures. The dependent variables are input performance, motor execution load, and user experience, which were measured through the following approaches:

- **Input performance:** Input performance is evaluated through **error rate** and **speed**, calculated by the record of keystrokes. The unit of speed is characters per minute (CPM). Considering the varying usage of each finger in the typing task, we use **erroneous finger pair frequency** to analyze the relationship between errors and specific fingers. This parameter is calculated by dividing the number of incorrect inputs made with these paired fingers by the total number of input events attempted with them. It's important to note that two-handed errors (e.g., b(LH)a(RH)) identified in this study were excluded from the subsequent analysis, which specifically focused on left/right-hand (e.g., b(RH)c(RH)) errors. The paired fingers combination is marked as RH-bc for conciseness.
- **Motor execution load:** During the task, motor execution load was measured using a wired fNIRS system (Shimadzu labnirs). As shown in Figure 9, the probes consist of 15 infrared light sources and 15 detectors arranged in 45 data channels (CH1 to CH45), mainly covering the Pre-Motor and Supplementary Motor Cortex (i.e., Brodmann 6 region), the Primary Motor Cortex (i.e., Brodmann 4 region), and part of the Primary somatosensory cortex. Near-infrared light was emitted (with wavelengths of 780 nm, 805nm, and 830 nm) from an emitter and received by a nearby detector to form a channel. The distance between the emitters and detectors was 35 mm. Each channel reports two measurements: HbO (oxygenated hemoglobin) and HbR (deoxygenated hemoglobin). The data was recorded at 22 Hz.
- **User experience measure:** The NASA-TLX [27] was used to assess the participants' subjective perceived mental workload. An informal conversation with the participants was followed to obtain their more detailed subjective feedback on the system and task.

5.3.3 Procedure. After obtaining informed consent, the participants received detailed information about the study's aim and procedures. They sat in armless chairs and completed training blocks. Subsequently, the fNIRS device was fitted to ensure comfort before the formal experiment. The entire task unfolded within a virtual scene presented through a VR headset (Quest 2). In this scene, depicted in Figure 8, a canvas at the top displayed the input sentence, while the reference text appeared in the middle. Incorrect characters were highlighted in red to alert the participants. At the bottom of the scene, a standard QWERTY keyboard and a pair of virtual hands representing characters were featured. The keyboard is 253∗79∗5mm with 24mm round keys. During the training stage, the participants set the position of the keyboard according to their typing habits, as in Study 1. They were instructed to use all eight fingers for input, with the activated keys turning blue.

Each participant completed four trials, each comprising a 30-second resting state phase followed by a 180-second task phase. During the resting state, the participants were required to remain calm and refrain from any movement, while during the task phase, they were instructed to type as quickly and accurately as possible. After each trial, a 120-second rest period followed, during which the participants either wore or removed the coactivation intervention apparatus based on the trial condition. The experimental task was conducted in low-light conditions to mitigate the influence of ambient light on the fidelity of fNIRS signals [63]. Upon completion of all blocks, the participants filled out a questionnaire (NASA-TLX) to assess their subjective experiences.

5.3.4 fNIRS Data Processing. The fNIRS data was analyzed using Shimadzu LabNIRS and NIRS KIT [30]. At first, the raw signals were converted to optical density changes and then to HbO and HbR estimates using Beer-Lambert law in the Shimadzu LabNIRS. The

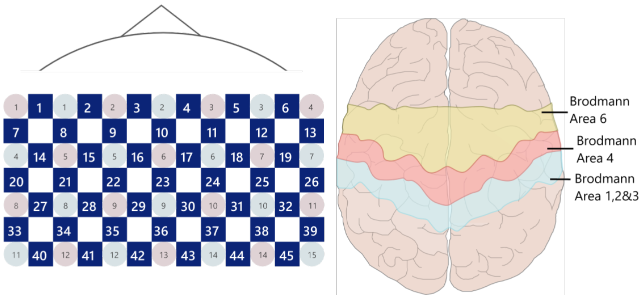

Figure 9: Probe Distribution Configuration in LabNIRS software (Circles indicate probes, squares denote channels), showcasing Brodmann Areas coverage on the right.

Table 1: The regions of interest and correlative channels.

ROI	Channel	Cortical Area	Brodmann Area	Hemisphere
SC1	9, 15, 22	Pre-Motor and		Left
SCz	10, 16, 17, 23	Supplementary Motor	6	Medial
SC2	11, 18, 24	Cortex		Right
C1	21, 28	Primary Motor		Left
Cz	29, 30, 36	Cortex	4	Medial
C2	25, 31			Right
S1	20, 27, 33	Primary Somatosensory	1,2&3	Left
S2	26, 32, 39	Cortex		Right

subsequent procedures were then conducted at the NIRS KIT. We used the Temporal Derivative Distribution Repair (TDDR) method to correct motion artifacts [16] and a third-order Infinite Impulse Response (IIR) filter to select signals between specific frequency bands by using bandpass filtering from 0.01 to 0.08 Hz. In the individual-level analysis, the General Linear Model (GLM) approach detects task activation (i.e., estimate beta values). For group-level analysis, the paired t-test was performed to assess significant differences in beta values among channels between the two conditions. To better distinguish cortical arousal, nine regions of interest (ROIs) were defined based on previous work [87], and the average beta values of channels within each ROI were calculated. Illustrated in Table 1, the motor cortex was divided into six ROIs according to anatomical structures, and two ROIs covered the somatosensory cortex due to probe limitations.

5.4 Results

5.4.1 Input performance. A Wilcoxon signed-rank test revealed that restraining finger coactivation has no significant effects on input speed (CON-1 [Mdn = 93], CON-2[Mdn = 86, p = 0.951]). For error rate, a paired t-test showed that it is significantly lower in CON-2 compared to CON-1 (CON-1 [Mean ± SD = 4.67% ± 2.13%], CON-2 [Mean ± SD = 2.64% ± 1.30%], t = 5.119, p < 0.001).

In CON-1, we recorded 5,402 correct input events and 255 errors. Among these errors, 31.7% stemmed from erroneous finger pair on the left hand, while 22.7% originated from the right hand. In CON-2, there were 5,496 correct inputs and 147 errors. Here, the left-hand erroneous finger pair accounted for 26.5% of errors, while the right-hand erroneous finger pair contributed to 15.6%. Subsequently, we examined the error rates for both left and right hands using the Wilcoxon signed-rank test. Restraining finger coactivation led to reduced error rates, evident in both the left (CON-1 [Mdn = 1.22%], CON-2 [Mdn = 0.53%], Z = -3.490, p = 0.001) and right (CON-1 [Mdn = 0.68%], CON-2 [Mdn = 0.53%], Z = -2.535, p = 0.011) hands. Additionally, a significant difference in error rates between the left (Mdn = 1.22%) and right (Mdn = 0.68%) hands was observed (Z = -2.053, p = 0.04), exclusively in CON-1. The inter-key interval between the left hand and right hand showed no significant difference.

Errors in mid-air typing can be categorized into spelling errors and coactivated errors [17]. Instead of the motor control errors in Study 1, here the spelling errors are prominent in this study and are generally unrelated to finger coactivation. This is due to the typing task does not require intense movement, but rather a planned order of keystrokes. The proportion of coactivated errors in total errors decreased from 35.29% in CON-1 to 20.41% in CON-2. In comparison to CON-1, coactivated errors for both the left (CON-1 [Mdn = 0.76%], CON-2 [Mdn = 0], Z = -3.375, p = 0.001) and right (CON-1 [Mdn = 0.38%], CON-2 [Mdn = 0], Z = -2.385, p = 0.017) hands were significantly reduced in CON-2. In addition, the right-hand (Mdn = 0.38%) coactivated error is less than the left-hand (Mdn = 0.76%, Z = -2.012, p= 0.044) without restraining activation. We count the erroneous finger pair frequency of the specific paired finger in all input events, shown in Fig 10, and the margin between CON-1 and CON-2, sorting in descending order, are LH-cd (10.7%), LH-bc (10.7%), RH-bc (10.2%), LH-bd (3.5%), RH-ac (3.4%), RH-cb (3.3%), LH-ba (3.1%) and LH-ab (2.7%).

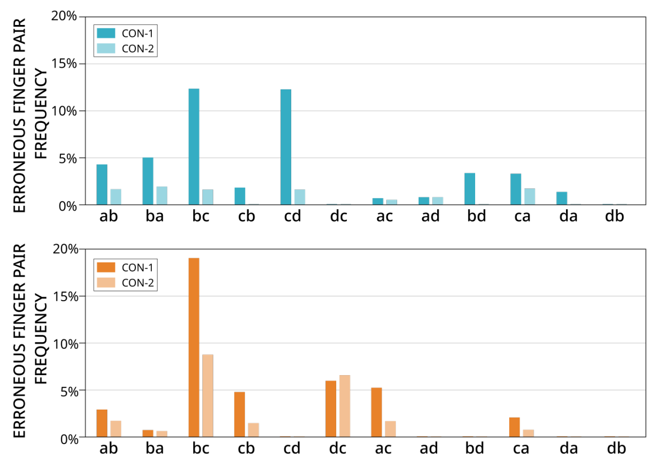

Figure 10: Frequency of erroneous finger pair in CON-1 and CON-2. Above: Pairings for the Left Hand. Below: Pairings for the Right Hand. Finger pairs used less than 30 times in total are excluded from the analysis.

5.4.2 fNIRS result. To investigate the finger coactivation-associated effect on the activation of cortical regions, we carried out a three-way repeated measures ANOVA with within-subject factors CON (without vs. with the coactivation intervention apparatus), BA (ROI SC1/SC2, ROI C1/C2, and ROI S1/S2), and HEMI (left vs. right).

Table 2: Results from Pairwise Comparisons in Repeated Measure ANOVA with Three and Two Factors.

	ROI	Mean±SE		Difference	p	95% CI
Pairwise comparsion of BA in three-way repeated measure ANOVA						
[CON-1, BA=6, left]	SC1	$-1.73 \times 10^{-4} \pm 1.21 \times 10^{-4}$		2.84×10^{-4}	0.023	$3.358 \times 10^{-5}, 5.35 \times 10^{-4}$
[CON-1, BA=4, left]	C1	$1.11 \times 10^{-4} \pm 1.17 \times 10^{-4}$				
Pairwise comparsion of HEMI in two-way repeated measure ANOVA						
[CON-1, left]	C1	$2.14 \times 10^{-4} \pm 9.3 \times 10^{-5}$	C1 vs. C2	4.19×10^{-4}	0.034	$2.6 \times 10^{-5}, 8.13 \times 10^{-4}$
[CON-1, right]	C2	$-2.05 \times 10^{-4} \pm 1.75 \times 10^{-4}$				
[CON-1, medial]	Cz	$-4.64 \times 10^{-4} \pm 1.78 \times 10^{-4}$	C1 vs. Cz	6.78×10^{-4}	0.001	$2.69 \times 10^{-4}, 1.09 \times 10^{-3}$
Pairwise comparsion of CON in two-way repeated measure ANOVA						
[CON-1, left]	C1	$1.09 \times 10^{-4} \pm 1.13 \times 10^{-4}$	CON-1 vs. CON-2	2.35×10^{-4}	0.012	$5.7 \times 10^{-5}, 4.12 \times 10^{-4}$
[CON-2, left]	C1	$-1.26 \times 10^{-4} \pm 1.30 \times 10^{-4}$				

Table 3: Results of paired t-test of the beta values of channels grouped by CON.

	Channel	t	p	Cortical Area	Brodmann Area	Hemisphere
CON-1 vs. CON-2	ch26	-2.056	.051	Primary Somatosensory Cortex	1, 2&3	R
	ch28	2.219	.037	Primary Motor Cortex	4	L

Illustrated in Table A1, the ANOVA revealed a significant three-way interaction effect of CON∗ BA∗HEMI (df = (2, 34), F = 6.501, p = 0.004, η^2 = 0.277). Further simple effects testing revealed significant two-way interaction effects - CON∗HEMI and BA∗HEMI. The interaction effect CON*BA only showed significance at the left hemisphere level. Further, BA showed a significant simple main effect for CON-1. The results of the above main and simple effects are shown in the Appendix Table A1. Depicted in Table 2, post hoc tests (Bonferroni) showed stronger increases (p = 0.023) in the Pre-Motor and Supplementary Motor Cortex region (SC1) compared to the Primary Motor Cortex region (C1), while Somatosensory Cortex region (S1) had no significant difference compared to the above regions.

The overall results indicated a difference in activation between the two components of the Motor Cortex. To analyze the Motor Cortex deeply, a two-way repeated measure ANOVA with within-subject factors CON (without vs. with the coactivation intervention apparatus) and HEMI (left, medial, and right) was applied to the Primary Motor Cortex region (ROI C), and Pre-motor and Supplementary Motor Cortex region (ROI SC), respectively. The two-way interaction effect CON∗HEMI (df = (2, 38), F = 7.592, p = 0.002, η^2 = 0.286) was significant in ROI C. For CON-1, the activation of the left hemisphere (C1) is higher than C2 (p = 0.034) and Cz (p = 0.001), illustrated in Table 2. There is no significant difference between hemispheres for CON-2, which is consistent with the above results of the three-way repeated measures ANOVA. The detailed proof is given in Appendix Table A2. In addition, post hoc tests (Bonferroni) revealed that activation was lower (p = 0.012) in CON-2 than in CON-1 in the left hemisphere, which gave rise to a significant simple effect of CON. In ROI SC, no significant differences were found at the hemispheres or CON level. As shown in Table 3, the paired t-test revealed the activation of channel 28 was significantly lower after restraining finger coactivation, which confirmed a substantial decrease in ROI C1. Moreover, channel 26 weakly increased with the coactivation intervention apparatus, which indicates tactile sensation may exist during the wearing apparatus.

In summary, there was a reduction of activation in the Pre-Motor and Supplementary Motor Cortex region in the left hemisphere after restraining finger coactivation, which eliminated the difference between hemispheres.

5.4.3 *Questionnaire result.*

Paired t-tests were performed on the data. The two conditions regarding physical demand and temporal demand were similar. For mental demand, scores of CON-2 were significantly lower than CON-1 (CON-1 [Mean ± SD = 9.7 ± 3.8], CON-2 [Mean ± SD = 7.3 ± 2.8], t = 3.334, p = 0.007). For performance, scores were also significantly lower compared to CON-2 with CON-1 (CON-1 [Mean ± SD = 11.6 ± 3.9], CON-2 [Mean ± SD = 7.9 ± 2.4], t = 3.455, p = 0.005), which is consistence with behavior results. The participants felt less effort (CON-1 [Mean ± SD = 11.7 ± 4.0], CON-2 [Mean ± SD = 7.3 ± 2.8], t = 4.862, p = 0.001) was required in CON-2 and less frustrated (CON-1 [Mean ± SD = 10.8 ± 3.8], CON-2 [Mean ± SD = 6.8 ± 3.4], t = 3.03, p = 0.011) because of good task performance.

5.4.4 *User Feedback.*

When asked to compare their performance between the two typing conditions (i.e., with and without restraining finger coactivation), the participants provided the following comments: 'Using the intervention apparatus reduced my tendency to press multiple fingers simultaneously, which made me feel that my ring fingers were more independent' (P5), 'restraining finger coactivation gave me a growing sense of ease and made it feel as though I didn't need to consciously control my fingers during the pressing process' (P8), and 'my fingers aren't syncing up as they used to, which helps me make fewer mistakes when typing on the keyboard' (P1). Additionally, two participants reported feeling kinesthetic feedback while restraining finger coactivation, which they found to be more reliable compared to not restraining: 'The sensation of pressing down with this apparatus felt distinct from

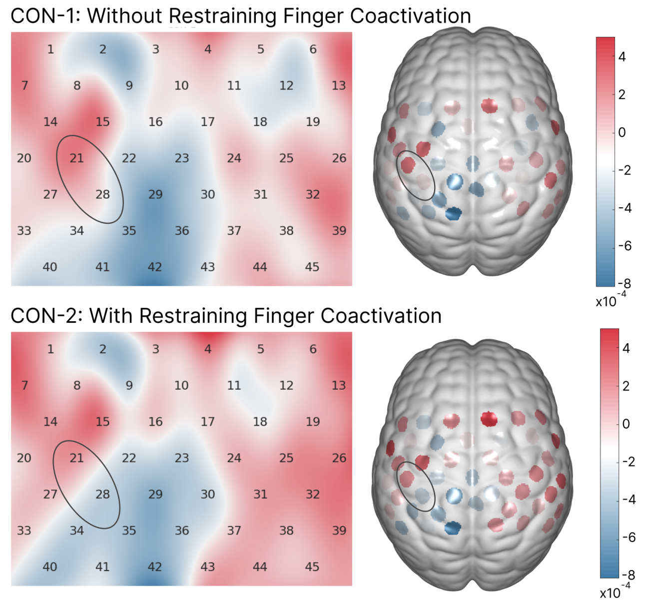

Figure 11: Activation across channels depicted with both 2D and 3D distributions. Redder colors denote high activation, while bluer hues indicate low activation. The grey circle highlights ROI C1. This region exhibited a notable decrease during finger coactivation restraint (CON-2) compared to its absence (CON-1).

the absence of resistance when typing freehand' (P7), and 'when my finger coactivation is restraining, I find my actions to be more reliable—I don't have to worry about accidentally hitting the keys' (P2). This suggests that providing motor constraints gives a more reliable sense of motor control and a positive user experience.

5.5 Experiment Discussion

In the preceding experiments, we collected behavioral and hemodynamic data to assess input performance, motor execution load, and subjective experiences during mid-air typing. This section discusses the mechanism of restraining finger coactivation and compares it with the results of Study 1.

5.5.1 Overall statement. The findings of the study confirm that restraining finger coactivation effectively lowers the error rate without compromising input speed in mid-air typing, and it lessens the burden on motor execution. The incidence of involuntary movements caused by coactivation saw a significant reduction in both hands. As a result, under the CON-2, the proportion of coactivation errors in total errors was nearly halved.

The study also revealed a reduction in spelling errors, despite the coactivation intervention apparatus targeting only the suppression of finger coactivation, as well as the reduction of motor control errors in Study 1. This suggests that the effort not spent on consciously controlling involuntary finger movements might be redirected toward managing other finger actions, such as hand coordination. According to the NASA-TLX questionnaire results, there was a reduction in mental effort, implying that the conserved mental resources could be allocated to cognitive tasks, such as planning finger sequence. This will require a quantitative evaluation of the hemodynamics of the frontal lobe in the future.

5.5.2 Cortices arousal. In terms of neural results, it was observed that restraining coactivation can reduce excitability in the motor cortex (ROI C1). Under CON-1, the Primary Motor Cortex of the left hemisphere exhibited more activity than other areas. In this state, without coactivation constraints, the activation levels in the left, medial, and right hemispheres showed significant differences, with the left side being markedly higher. However, upon restraining coactivation, activity in this area significantly decreased, aligning with the levels in other hemispheres without notable differences. This suggests that restraining both hands' coactivation to prevent unintended typing errors demands considerable neural resources from the left Primary Motor Cortex, resulting in significantly higher activity compared to other motor regions. This observation aligns with Amunts et al.'s [1] findings, indicating that the motor cortex in the brain area opposite the dominant hand is engaged in motor control of both hands. As mentioned earlier, pianists exhibited lower levels of cortical excitability during tasks involving active suppression of finger coactivation compared to non-musicians. This advantage is attributed to training in finger independence, implying that the coactivation intervention apparatus can achieve a similar effect at the neuro-mechanical level as training for finger independence.

5.5.3 Results compared to Study 1. Although the error rate for cyclic movements is approximately five times higher than for discrete movements, the error rates decreased similarly. After restraining finger coactivation, the error rate for cyclic movements on the right hand decreased from 23.3% to 13.4% for Seq. 3, and decreased from 17.7% to 11.1% for Seq. 4. In discrete movements, the error rate decreased from 4.67% to 2.64%.

A notable discrepancy between the results of the two studies lies in the performance of the left hand, which did not exhibit significant improvement in Study 1. It may be attributed to the overly cautious strategy employed when using the non-dominant hand for maximal rate tapping in Study 1, resulting in slower speeds, lower error rates, and consequently, fewer coactivated errors. Conversely, Study 2 observed a similar frequency of coactivated errors in both hands, along with improvements in involuntary movements.

In both studies, errors involving adjacent finger pairs decreased more than those involving non-adjacent pairs. This illuminates how restraining coactivation improves motor performance, primarily by reducing involuntary movements of finger pairs, especially the middle-ring finger pair, potentially due to their lower independence index, as measured in Section 3.2. Non-coactivated errors were observed in both studies. The fNIRS results confirmed that restraining finger coactivation reduced motor executive load. In Study 1, conserved neural resources helped mitigate motor control errors in highly independent fingers. In Study 2, this reduction in motor executive load contributed to fewer spelling errors, as reflected in the decreased error rates on both hands. Specifically, the error rate for middle-pinky finger pairs on the left hand and index-ring finger pairs on the right hand declined, likely due to fewer spelling errors rather than coactivated movements (i.e., mispresses).

6 IMPLICATIONS & INSIGHTS

Drawing from our findings and considerations, we explore the implications and insights of this study on mid-air typing. The results highlight the benefits of incorporating motor constraints and neuromechanical insights into the design of more natural and efficient spatial interactions.

6.1 Optimizing Mid-air Typing Sequences

Mid-air typing plays a pivotal role in a range of virtual applications, including playing musical instruments, rehabilitation training, and text input within virtual reality (VR) environments. An essential aspect of designing these tasks is to configure the motion tasks for finger movements, to avoid sequences prone to errors. Strategies include minimizing movements across non-adjacent fingers in series considerations for the speed among different target sequences. Our findings indicate that the average speed for tapping a simple sequence in a minimal virtual reality (MVR) setup is 147.6 CPM, while for complex typing tasks, it reduces to 93 CPM.

Notably, coactivation, particularly involving the middle finger, demands attention. Visual cues and the layout of the virtual keyboard can enhance typing performance [72, 88]. This approach may be used to reduce the use of the middle finger, thus minimizing coactivated errors. Moreover, algorithms designed to automatically rectify coactivation errors can specifically target the voluntary movements of the middle finger followed by the movements of the ring finger. Our data show a coactivated error rate of approximately 12.5% for the left hand and 18% for the right, which can be decreased to 3% and 8%, respectively, under optimal conditions. These benchmarks are critical for algorithm performance, highlighting the importance of balancing error correction without overfitting, which could misinterpret valid inputs.

6.2 Intervening Mid-air Typing with Kinesthetic Devices

We advocate for employing kinesthetic devices for typing in mid-air. This intervention directly amends user behavior, enhancing task performance and diminishing the motor executive load on brain activity. Numerous studies have proposed viable technical solutions utilizing various types of braking mechanisms, including electromechanical [75, 78], pneumatic [8, 95], passive locking mechanisms [51, 52], and Electrical Muscle Stimulation (EMS) [53, 73], among others. These techniques can also adapt to mitigate finger coactivation and enhance mid-air typing, compensating for the limitations of our current apparatus, which prevents two fingers from moving simultaneously and is used solely for study purposes. Additionally, the passive interlocking mechanism developed and utilized in our research can seamlessly integrate with the aforementioned exoskeletons without requiring additional energy.

Some exoskeleton gloves restrict movement in all hand joints to maximize effectiveness. This necessitates further consideration of the mechanical redundancy inherent in the device. An essential question to address is which natural articulation is within the hand. The human finger comprises three joints, namely the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints, in a sequential arrangement from the palm towards the fingertip direction. These joints have mechanical linkages among the extrinsic muscles. The range of rotation for the metacarpophalangeal (MCP) joint is 90° of flexion and 45° of hyperextension when using the metacarpal bone as a reference surface [28]. There is a strong correlation between the angles of the proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints, forming an S-shaped curvature [82]. Certain exoskeletons enforce particular hand postures on users to mimic grasping a virtual object by flexing all joints. However, restricting movement in the distal interphalangeal (DIP) joint is unnecessary since it flexes synergistically with finger flexion. In our experiment, we selected the metacarpophalangeal (MCP) joints with the highest degree of coactivation. Our findings demonstrate that this approach effectively reduces coactivation. Thus, designers of exoskeletons aiming to minimize mechanical redundancy should integrate the limitations of natural hand joints with the motor constraints imposed by the exoskeletons.

6.3 Providing motor constraints in spatial interaction

Introducing physical tools to enhance mid-air interaction quality is a common framework in virtual interaction. These tools are typically auxiliary and easily manipulated. Besides their input and output functionality, the mechanism by which physical tools contribute to good user experience and task performance is not discussed in depth.

For example, enabling VR users to type on a physical surface is also deemed promising and feasible because the surface offers tactile feedback of keystrokes [33, 54]. However, while tactile feedback on fingertips aids in indicating the current position of the fingers for users, it does not facilitate the clicking movement after the finger has reached the target position [58], due to finger coactivation problems as discussed, owing to finger coactivation issues as discussed. The motor constraints imposed by physical surfaces on the user are seldom recognized and assessed. Virtual interaction removes spatial limitations compared to the physical world, as well as the natural motor constraints associated with interacting with physical objects. However, current interactive device designs in VR primarily focus on replicating physical objects and their manipulations. Considering motor constraints could assist in identifying object properties directly linked to interactive habits and aid in the development of devices that are more applicable to spatial interaction.

Three suggestions are proposed for designing mid-air interaction tools: 1) implementing necessary constraints on joints with high degrees of freedom to improve interactive performance; 2) utilizing inherent neuromechanical constraints on fingers to simplify device design; 3) increasing monitoring of neural activity to discern differences between real-world and VR interactions. Practically, these tools can be utilized for isolated finger training, benefiting piano players or those undergoing finger rehabilitation. The restraint level can be adjusted to create varying levels of training difficulty. The motor constraints lower the motor executive load, assisting individuals with neurological challenges in finger control.

In summary, the influence of motor constraints on both peripheral and central nervous systems is essential and may serve as a guideline for enhancing virtual training and spatial interaction.

7 DISCUSSION, LIMITATION, AND FUTURE WORK

This work examines the effects of mitigating finger coactivation on the performance and user experience of rapid finger-tapping and ten-finger typing in mid-air, offering insights for developing intervention methods for such spatial interactions. Finger coactivation, a significant hindrance in mid-air typing tasks, has been widely noted yet under-explored by interaction researchers and designers. This study introduces the application of motor constraints to reduce finger coactivation in a mid-air typing context, analyzing its impact from a neuromechanical perspective.

We evaluated cyclic sequential movements in a finger-tapping task. For complex and error-prone sequences involving non-adjacent finger movements, suppressing coactivation corrects errors based on the middle finger's action, particularly between the middle-ring fingers, both ulnar-radially and vice versa, aligning with findings that coactivation predominantly occurs between adjacent fingers [43]. However, this approach did not enhance the accuracy of simple sequences, suggesting the need for further investigation into how motor sequence complexity affects coactivation. Concerning multi-finger input tasks, an essential consideration is the potential detriment of co-activation restraint on input speed. Fortunately, restraining coactivation did not decrease typing speed while it did lower error rates. Moreover, at the central nervous system level, there was a noticeable decrease in motor executive load, evidenced by reduced oxygen consumption in the Primary Motor Cortex's left hemisphere. The NASA-TLX results further affirm that restraining finger coactivation lowers mental demand, effort, and frustration, suggesting that the conserved neural resources contribute to reducing motor control errors and spelling errors, a hypothesis requiring further exploration.

This study employed text material consisting of a 250-character essay. Despite manual proofreading to enhance comprehensibility, the text retained semantic content, potentially leading to varied interpretations among subjects and influencing their execution of movement sequences. Future studies might employ randomly generated character sequences as nonsensical words to mitigate the influence of semantic interpretation on the execution of movements. Additionally, as there is no requirement for equal finger usage in text allocation, some finger pairs were used infrequently, making valid data unavailable to observe the impact of restraining finger coactivation on these pairs. Furthermore, the hand-to-keyboard distance may impact mispresses. A long travel distance requires a longer inter-key interval, which can slow typing speed and potentially eliminate mispresses. Another factor not included in our study is the lateral motion of a finger when stretching it to arrive at a far key, which makes the other fingers tend to curl. How such factors could affect the detection of finger coactivation is worth exploring in future studies.

The intervention method employed in this experiment entails restraining neighboring fingers. Furthermore, various other intervention methods can be employed to diminish finger coactivation. For example, slower finger movement may be applicable, as research indicates that finger coactivation is less common at a tapping frequency of 2Hz than at 3Hz [26]. Another potential intervention involves restricting the angular motion of voluntary finger bending, as finger coactivation tends to be absent when the voluntary fingers are slightly bent. However, these alternative methods were not utilized in our study due to concerns about their potential influence on the motor typing behavior of the subjects. In our studies, the participants did not report fatigue, likely due to the short tasks. However, mid-air typing is not a short-term interactive behavior, and the intervention method must avoid introducing potential fatigue.

Although hemodynamic outcomes indicated that tactile stimulation by the apparatus did not significantly activate the somatosensory cortex, it is crucial to recognize that tactile sensation affects sequential decision-making. That is, tactile and proprioceptive feedback collectively inform finger positioning and subsequent movements [83], emphasizing the role of sensory feedback in closed-loop control. Some mid-air typing interventions employ physical boards to provide natural tactile feedback and motor constraints, demonstrating effectiveness. This approach, compared to simple coactivation restraint, involves more complex interactions between haptic feedback and motor constraints, warranting future investigation.

To our knowledge, this is the first HCI study to systematically apply motor constraints to finger coactivation and assess its neuromechanical benefits for mid-air typing. The findings reveal that restraining coactivation among adjacent fingers significantly reduces both mispresses and motor control errors in sequential tapping and typing spelling errors. This improvement is attributed to a lower motor executive load, suggesting that finger coactivation exacerbates motor control loss. The loss of motor control prevents the fingers from executing sequences accurately, hindering mid-air typing and thereby leading to a suboptimal user experience. These positive outcomes highlight the potential of intervention methods in improving spatial interactions.

8 CONCLUSION

This study addresses the issue of finger coactivation, which is believed to impair mid-air typing performance. In this study, we utilized a device to restrain finger coactivation, exploring its impact on mid-air typing performance and neural resources involved in motor control from a neuromechanical standpoint. Our findings indicate that restraining finger coactivation enhances mid-air typing capabilities by reducing mispresses, motor control errors, and spelling errors considered non-coactivated errors. Additionally, the reduction in motor executive load suggests this approach conserves neuronal resources, potentially enhancing motor control and cognitive functions, thereby reducing errors and lowering subjects' mental demands and frustration. This paper also provides insights into the design of kinesthetic devices for mid-air typing and improves user experience-related spatial interactions, focusing on motor constraints.

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A APPENDIX: TABLE

Table A1: Results of three-way repeated measure ANOVA.

		df	F	p	η^2
Interactions					
CON*BA*HEMI		2, 34	6.501	0.004	0.277
CON*HEMI		1, 17	4.591	0.047	0.213
BA*HEMI		2, 34	4.309	0.021	0.202
Simple interactions and simple main effects					
BA*HEMI[CON-1]		2, 34	6.738	0.003	0.284
BA[CON-1, left]		2, 42	5.033	0.011	0.193
Pairwise comparsion	**ROI**	**Mean±SE**	**Difference**	p	**95% CI**
[CON-1, BA=6, left]	SC1	$-1.73 \times 10^{-4} \pm 1.21 \times 10^{-4}$	2.84×10^{-4}	0.023	$3.358 \times 10^{-5}, 5.35 \times 10^{-4}$
[CON-1, BA=4, left]	C1	$1.11 \times 10^{-4} \pm 1.17 \times 10^{-4}$			

Table A2: Results of two-way repeated measure ANOVA on Primary Motor Cortex.

		df	F	p	η^2	
Interactions and main effects						
CON*HEMI		2, 38	7.592	0.002	0.286	
HEMI		2, 38	4.315	0.02	0.185	
Simple effects						
HEMI[CON-1]		2, 38	9.487	0.001	0.333	
CON[left]		1, 22	7.528	0.012	0.255	
	ROI	**Mean±SE**		**Difference**	**p**	**95% CI**
Pairwise comparsion						
[CON-1, left]	C1	$2.14 \times 10^{-4} \pm 9.3 \times 10^{-5}$	C1 vs. C2	4.19×10^{-4}	0.034	$2.6 \times 10^{-5}, 8.13 \times 10^{-4}$
[CON-1, right]	C2	$-2.05 \times 10^{-4} \pm 1.75 \times 10^{-4}$				
[CON-1, medial]	Cz	$-4.64 \times 10^{-4} \pm 1.78 \times 10^{-4}$	C1 vs. Cz	6.78×10^{-4}	0.001	$2.69 \times 10^{-4}, 1.09 \times 10^{-3}$
[CON-1, left]	C1	$1.09 \times 10^{-4} \pm 1.13 \times 10^{-4}$	CON-1 vs. CON-2	2.35×10^{-4}	0.012	$5.7 \times 10^{-5}, 4.12 \times 10^{-4}$
[CON-2, left]	C1	$-1.26 \times 10^{-4} \pm 1.30 \times 10^{-4}$				