Age-related Facilitation of Bimanual Finger Behaviors by Haptic Augmentation

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Abstract

Proficient use of multiple fingers across both hands to manipulate objects empowers our daily interactions with the world. Gaining dexterity in performing delicate tasks with both hands can take weeks to years to master. The goal of this study is to understand if simple mechanical abstraction could improve performance on bimanual response time to visual stimuli, using index fingers and thumbs. A plate placed over the buttons was introduced to induce a new conceptualization of the task, where instead of pressing buttons, the subjects were rocking a plate over them. We observed improved performance in bimanual actions but not in unilateral actions. In the group of middle-aged individuals, synchronous bimanual responses were enhanced with the use of this mechanical augmentation. This effect remained even after removing the plate. Conversely, within a group of younger adults, there was no observed effect. We believe that highly similar afferent sensory signals from the fingers of both hands change the motor control strategy. This work lays the groundwork for further research into understanding the rich variety of multi-fingered bimanual behaviors in both abstract and practical settings.

New & Noteworthy Mechanical coupling of hands improved bimanual choice response time in middle-aged participants, while young adult participants remained unaffected. The effect remained after removing the coupling.

Keywords keywordshuman performance augmentation, haptic augmentation, multi-fingered, bimanual, choice reaction time

Introduction

Human have based daily activities on the collaborative use of two hands [4]. Fingers across both hands are employed when dealing with fine manipulation tasks. Using a knife and

fork [19], playing musical instruments [10] or surgery [27] may need years of learning to achieve bimanual proficiency. Similarly, operators of articulated cranes or other complex man-machine control systems need to learn system specific bimanual control to be able to control all the degrees of freedoms to manipulate machine dynamics [43].

Complex fine manipulation, however, needs to overcome two major challenges: independent control of individual fingers [30], and independent control of each hand [24]. Achieving complete control over individual joints of each of the fingers is not only anatomically impossible but also exceeds the cognitive limits of human motor control capacity [39]. Controlling of two limbs simultaneously leads to competition of limited resources in the central nervous system (CNS) [40, 24]. This phenomenon, *bimanual interference* [23], appears as unwanted spatial and temporal coupling of the hands [20].

Acquiring bimanual proficiency is a gradual process [17]. It takes days to weeks to induce changes in nervous system to accommodate and integrate the new behaviors [34]. Learnt behaviors construct internal models that associate the actions with predicted sensory outcomes and are rapidly adapted to changes in internal and external conditions [46]. Apart from the quick adaptation to refine outcomes of behaviors, the manipulation of sensory feedback [28, 2] or the conceptualization of the task [41, 5, 18] during behavior can change the quality of the behavior. In this work, our goal is to investigate whether inducing a conceptual understanding of a task through mechanical abstraction can prompt immediate improvements in performance on a basic bimanual multi-fingered task.In a previous study on hemiparetic bimanual behaviors [22], we found indications that subjects may utilize a mental image of a single wheel while physically rotating two wheels independently with each arm. In this study, we aimed to advance the settings that would facilitate a more straightforward quantification of such conceptualization.

In this work, we adopted a response time test experiment where subjects were instructed to manipulate four symmetrically placed buttons in response to visual stimuli. First, subjects activated the buttons with four fingers, thumbs and index fingers, placed directly on the buttons. This was followed by a condition where a plate was placed over the buttons and thus the subjects were effectively rocking a plate to indirectly press the buttons. We hypothesized that this mechanical abstraction, as experienced by subjects without verbal explanation, would prepare the subjects to construct a new mental model of the task, and in this way to improve the response time. Next, we removed the plate to see if the possible conceptualization remained after removing the plate.

Response time (RT) is the time measured between a stimuli and an onset of an action. In *simple response time* (SRT) test, a subject has prepared motor commands, which are triggered by attended stimuli. The *Choice response time* (CRT) test is more complex as it involves target discrimination, response selection, response programming before the response can be initiated [7]. We selected the CRT as the main measure of performance, with the hypothesis that response selection and programming would be conducted more quickly due to the new conceptualization caused by the use of the plate.

Materials and Methods

Subjects Total of 43 subjects (age M=36.0, SD=10.8, male=24) were recruited for the experiments. The sample size was based on similar experiments measuring bimanual response times [49, 8]. The handedness was assessed with the short form Edinburgh handedness inventory [45]: Left=1, Mixed=4, and Right=38. Assessment of handedness comprised writing, throwing, toothbrush, and spoon. Scoring was 100 for "Always" and 50 for "Usually". Average scores less than 60, was rated "mixed handed". The experiment was exempted from approval by University of Eastern Finland Committee on Research Ethics because it did not meet any of the criteria defined by the Finnish Advisory Board on Research Integrity. The data was recorded in the year 2023.

Device A dedicated device was designed for registering the response time, see Figure 1 B. The device comprised four momentary tactile push buttons (diameter 6.5 mm, action 0.5 mm) in the square formation. Both the lateral and longitudinal distances between the centers of the buttons were set to 50 mm. During the experiments, one finger (thumb or index) was assigned to each buttons. The buttons were wired to an Arduino-compatible microcontroller that was registering the changes in button states and transmitting those to the host computer via serial connection. Host computer displayed stimuli, managed the experiment tasks, and logged the results.

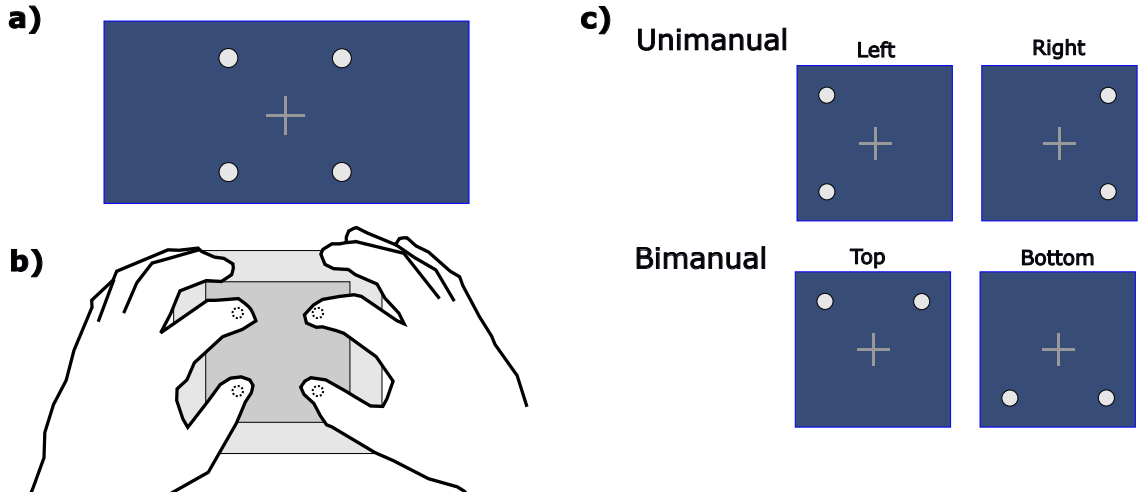

Figure 1: a) Stimuli display on computer screen with static fixation cross and four disks, which are shown or hidden to form stimuli variants. b) The device for registering the responses has four buttons, which are spatially associated with the disks on the stimuli display. One finger is allocated for each button. The buttons beneath the fingers are illustrated as circles drawn on the dashed line. The inner square illustrates a plate used in some of the tasks. c) The four different stimuli patterns used in two-finger tasks.

Plate To modulate changes in behavior, a 90x90 mm square plate was placed on top of the push buttons. The plate had cavities on the bottom surface that matched the buttons and stabilized the plate. The plate laid freely on the buttons, and pressing at the edge of the plate would cause it to fall out. The positions of the underlying buttons were marked with glue bumps on top surface of the plate, which allowed the fingers to be placed and kept on the location of the buttons without looking. During the use of the plate, the subjects mediated the button press by rocking the plate. The use of plate, however, required pressure from two fingers to activate the buttons below. When the plate was in use, the subjects were instructed to press the buttons like before, but this time with the plate between the fingers and buttons.

Stimuli and Response The subjects were instructed to place fingers to the buttons of the device and to fixate the gaze at a cross at center of the computer display. The stimuli was shown as flashing discs around the fixation cross in the square constellation, see Figure 1 a). Before each of the tasks, the buttons were connected to the feedback on the screen to help the subjects to establish the understanding between stimuli and response. During a trial, the stimuli was visible for 200 ms and the interval between onset of stimuli was random between 1200 to 2600 ms.

The subjects were instructed to respond with the buttons as quickly as possible and to ignore possible wrong responses. If response time was longer than 600 ms or contained wrong buttons, the trial was queued at the end of task-list to be repeated later.

Protocol The experiment session commenced with single-finger SRT task. The task consisted of 10 trials for each button in order top-left, top-right, bottom-left, and bottom-right. The subjects were asked whether they felt comfortable with pressing the device with each finger and they were monitored that they could provide timely response. The initiation of each new task was confirmed by subjects. Between the tasks, the subjects were corrected for finger placements and encouraged to find comfortable posture. Figure 2 illustrates the protocol of the experiment session together with the example of registered data.

The rest of the session contained three conditions: *Before*, *Plate*, and *After*. The plate was presented in the middle condition, the other conditions did not involve the plate. Each condition started with a SRT task and was followed by a CRT task. Each SRT task was repeated 10 times in order: Left, Top, Right, Bottom. The CRT tasks contained 40 repetitions for each of the previous tasks in randomized order.

After the session was completed, the subjects assessed the manipulation with the device and plate: ”Did you feel a difference between the trials using the additional plate and without the plate with scale 1 (no difference) to 10 (totally different)?” and ”Which one did you prefer: with the plate or without the plate”. The participants agreed that feeling was different with and without the plate M=6.5, SD=1.6. Total 24 participants (56%) preferred the interaction with the plate.

Data registration The data recording consisted of two types of response times: the reaction time and the desynchrony time. The *reaction time* (RT) was calculated as the

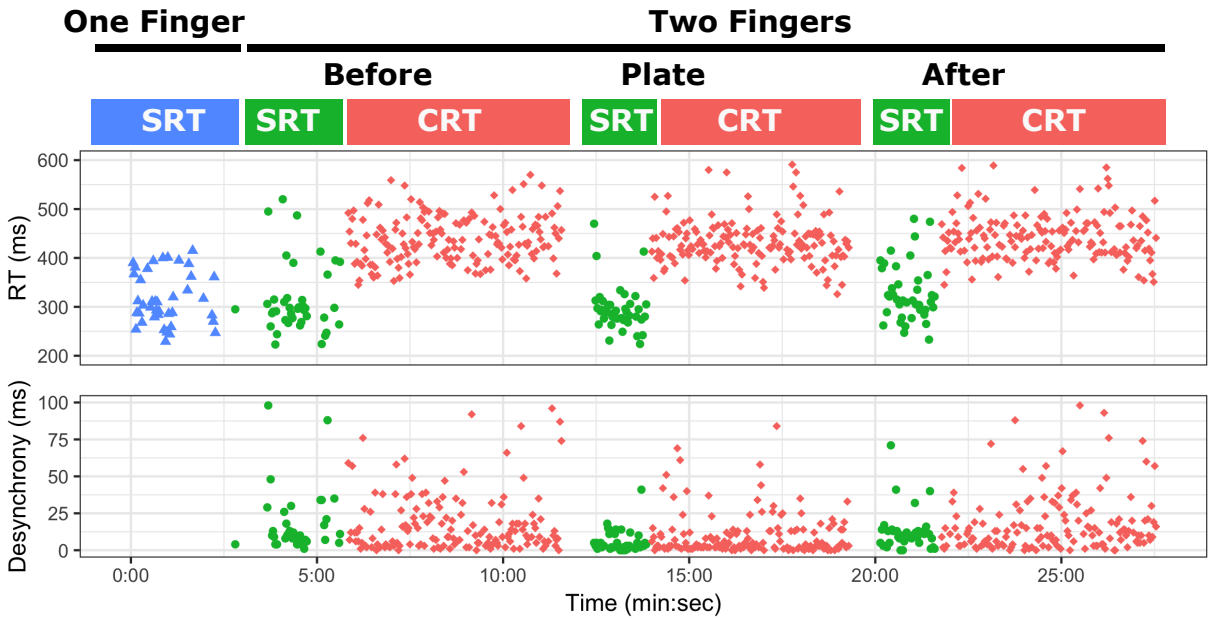

Figure 2: Full protocol sequence with the example registered data. The session was initiated with single finger SRT tasks on each four buttons of the device. Two-fingered SRT and CRT tasks were executed under three conditions: Before, Plate, and After. The plate condition is characterized by the use of the plate positioned over the buttons to mediate the responses. The registered data included response times (RT) and desynchrony, the timing difference in two-finger responses.

difference between the time from the onset of the stimulus and the time when all required buttons were pressed. If any other button was pressed the trial was automatically rejected and repeated again at the end of sequence. The responses with the reaction time shorter than 150 ms were rejected due to subject's anticipation. The *desynchrony time* was calculated as the difference between the time from the first contact with the button to the time when both required buttons were pressed. The responses with desynchrony time longer than 100 ms were rejected. The experiment session lasted 28 min 40s on average (SD= 3 min 16s). The response times for subjects were aggregated as means over valid trials.

Data analysis Response times under different conditions were analysed with repeated measures ANOVA. When sphericity was violated (Mauchy's test $p < .05$), Greenhouse–Geisser correction was applied. Post hoc was performed using pairwise t-test with Bonferroni correction.

Transparency and openness We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study, and we follow JARS [3]. All data, analysis code, and research materials are available on request within the

limits of General Data Protection Regulation (GPDR) and participants' consents. Data were analyzed using R version 3.6.1 [37]. This study's design and its analysis were not pre-registered.

Results

In this work, we investigated how the introduction of plate would affect behavior in a multi-fingered bimanual manipulation task. The main outcome was measured as choice-response time (CRT). Single-response time (SRT) was measured for the reference to understand whether variation in different fingerings would affect the results. In bimanual trials, we also examined desynchrony (or the temporal difference between the button activations).

Responses before the plate intervention

When examining the single-finger condition, ANOVA revealed that activations performed with left hand fingers were 13 ms (SD=19.3) slower than the activations using right-hand fingers (F(3, 126)=11.84, p=.0001). The finding reflected the prevalence of right-handed participants in our sample [35]. There were no statistical differences in response times between the index fingers and thumbs.

The mean response time in the first two-finger SRT condition was 304 ms (SD=34.7), which was significantly (t(42) = 3.46, p = 0.001) slower to that of single finger task (M=293 ms, SD=25.7), which results from the higher biomechanical complexity when pressing two buttons simultaneously. The ANOVA between the two-finger trial patterns did not indicate statistical differences between hands or fingers, not in response time or in desynchrony.

According to ANOVA, CRT tasks during the first condition did not elicit statistical differences in responses between trial patterns. Table 1 summarizes the response times and desynchrony times in different conditions and trial patterns. Because two-finger left-hand and right-hand responses were similar, we could conclude that the mechanical and biomechanical execution during activations were similar enough so that we can merge those together as Unimanual activations. Similarly, we merged index finger and thumb activation as Bimanual activations (see Table 2).

Effect of the plate

The plate connects physically the fingers that activate the buttons. As a result, two-finger responses acted in synchrony which decreased the desynchrony times in both bimanual and unimanual activations (see Figure 3). The average change from the Before condition to the Plate condition in bimanual patterns was 3 ms (SD=5.3), ANOVA (F(2, 84)=37.85, p=.0001). The same change in unimanual patterns was 9 ms (SD=7.6), ANOVA (F(2,84)=48.62, p=.0001). In both cases, the desynchrony times in the Plate condition were significantly lower compared to Before (p= $3.4e-09$) and After (p=$7.1e-09$) conditions. The desynchrony times between Before and After conditions did not statistically differ. Finally, the proportion of correct responses did not significantly differ across the CRT conditions.

Task	Left				Right				Index Finger				Thumb			
Condition	RT		Desync		RT		Desync		RT		Desync		RT		Desync	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
SRT Single	300	26.8			286	28.2			292	26.1			295	28.7		
SRT Before	315	43.6	21	8.4	304	35.1	20	9.0	295	35.1	17	10.9	303	36.2	16	7.5
SRT Plate	334	36.2	12	8.9	311	39.8	10	7.2	304	42.0	12	8.2	303	37.4	13	9.6
SRT After	328	44.7	20	9.8	315	33.7	23	10.2	298	35.1	16	8.4	309	34.1	16	9.0
CRT Before	417	45.2	27	9.2	412	41.4	25	8.1	412	52.2	15	4.6	424	50.7	16	5.9
CRT Plate	412	39.2	17	7.6	413	37.7	17	7.1	413	47.4	12	7.0	414	46.4	14	7.9
CRT After	414	38.0	26	9.0	409	39.1	24	8.3	405	45.1	15	5.3	416	46.4	17	5.8

Table 1: Response times, RT (ms), and related desynchrony (ms) in task conditions and trial patterns.

Plate intervention and age

Contrary to our hypothesis, the response times in CRT did not exhibit any variation for the population as a single group. To examine differences further, subjects were divided into two subgroups based on their age [16]. Subjects between age $20 - 39$ were grouped as "Young" (n=22, age M=27.0 SD=6.1, male=11, handedness mixed=4, right=18) and "Middle aged" (n=21, age M=45.6 SD=4.5, male=13, handedness left=1 right=20). The overall average CRT of the Young group (M=401 ms, SD=44.5) was faster than the reaction times of the Middle-aged group (M=427 ms, SD=36.8); t(251)=-5.1, p= $6.318e - 07$). Figure 4 illustrates CRT in bimanual and unimanual responses in these groups.

In the Plate condition, the CRT was significantly reduced in bimanual activations in the Middle aged group (F$(2, 40)$=7.816, p=.001). RT significantly differed between the Before condition (M=440 ms, SD=44.2), the Plate condition (M=423 ms, SD=39.9), p=0.028, and the After condition (M=424 ms, SD=38.4) with p=.012. This indicates that that RT remained improved even after removing the plate.

In the case of the young subjects, the plate did not improve the response times. The mean response time with plate was slower, although not significantly. This was possibly reflected in subjects' subjective perception. After the experiment, the subjects evaluated whether they preferred the manipulation with plate or without the plate. In 55 % of the young participants preferred manipulation without the plate while the same opinion was lower in the elder group (33 %).

Figure 5 illustrates the correlation of CRT with age. The bimanual correlation dropped from the Before condition r(41)=0.54, p=.004 to r=0.36, p=.017 in the Plate condition and remained at r(41)=.45, p=.002 in the After condition. Comparison of correlations showed statistical difference between the Before and other conditions. The corresponding values for correlation of unimanual CRT with age was Before (r=.44, p=.004), Plate (r=.39, p=.009), and After (r(41)=.42, p=.005). Comparison of correlations were performed us-

Task Condition	Unimanual RT M	Unimanual RT SD	Unimanual Desync M	Unimanual Desync SD	Bimanual RT M	Bimanual RT SD	Bimanual Desync M	Bimanual Desync SD	All RT M	All RT SD	All Desync M	All Desync SD	Correct Responses M	Correct Responses SD
SRT Single	293	31.1							293	31.1			86	13.7
SRT Before	309	37.4	20	6.9	299	34.2	16	6.3	304	34.7	18	4.8	91	10.9
SRT Plate	322	34.4	11	5.9	303	36.7	12	7.0	313	34.2	12	5.6	86	13.1
SRT After	322	38.2	21	8.6	304	32.6	16	5.9	313	32.4	19	5.5	89	8.5
CRT Before	414	42.2	26	7.9	418	50.5	16	4.0	416	45.7	21	4.9	87	11.1
CRT Plate	413	37.2	17	6.7	413	46.1	13	6.5	413	40.9	15	5.5	85	11.7
CRT After	411	37.2	25	8.0	410	44.5	16	4.8	411	40.1	21	4.9	88	9.5

Table 2: Response times, RT (ms), and related desynchrony (ms) in task conditions grouped to unimanual, bimanual, and all trial patterns, and the ratio of correct responses (%) in task conditions.

ing the "cocor-library" [15]. The significance was judged by confidence intervals of 95% with a comparison of two overlapping correlations based on dependent groups with Zou's method [48].

Discussion

When designing the experiment, we hypothesized that augmenting the four-button interface with a plate would implicitly change the mental representation of the task from pressing two buttons to rocking a plate in one direction. This effect was more pronounced in the bimanual activations, with less impact on unimanual two-button activations. The use of the plate facilitated the action when both hands were acting symmetrically in the task. Our analysis demonstrated that the persistence of this phenomenon was related to age. The responses of the younger subjects were not influenced by the use of the plate. Due to the limited effect, we rejected the hypothesis regarding the changing mental representation and, instead, sought for an explanation in other dynamics within the sensorimotor system.

Facilitation of bimanual responses

We observed that the plate had an effect on bimanual behaviors; however, unimanual behaviors were not significantly facilitated. Therefore, we need to examine the mechanics of bimanual control for an explanation. The bimanual control is attributed to sensorimotor cortices controlling contra-lateral arms [36]. The arms reflect to ipsilateral sensorimotor cortices: stimulation on cortical areas cause movements of the limbs and the sensory stimulation of the arm cause responses in the cortex. The cortices are connected by corpus calloseum with both inhibitory and exhibitory pathways [44]. Both unimanual and

bimanual actions cause cortical activations on both hemispheres. The interactions are complex enough that bimanual cortical activations are not necessarily stronger than unimanual [26, 14]. The interhemispheric inhibition plays an important role in the control of bimanual movements [32, 21] Increasing evidence on participation of both cortical hemispheres in unilateral motion has led some researchers to speculate that unimanual motions are specific case of bimanual motions, where the opposing arm is inhibited [11, 6].

The bimanual motion pattern applied in the experiment were particularly easy to execute. Bimanual movements where contralateral homologous muscles contract simultaneously are more stable compared to other kinds of bimanual patterns [20]. The overflow of motor commands to involuntary synchronous contractions of opposite limb is known as *mirror movements* [12]. These movements are observed in childhood, but they diminish as the motor control develops. Weaker mirrored muscle activations, which do not necessary result motion, can also be observed in healthy subjects with the means of surface electromyography [12]. Task demand, fatigue as well as age are factors [9]. Elder persons, however, have been shown to be able to inhibit the mirror behaviors when they are aware of those [1]. During the CRT tasks in our study, the bimanual trials were mixed with unimanual trials. According to the result of correct responses in CRT, the bimanual responses did not interfere unimanual responses.

Role of aging

The facilitation of bimanual behaviors only appeared in the older subjects. We demonstrated this by splitting the subjects to two groups, “young” and “middle aged”, and also by correlating the response time by age. The human nervous system changes along with aging. Response times are slowing down, which is more profound in CRT than SRT [47]. Similarly, in our study, only CRT significantly correlated with subject’s age. Since visual stimuli and motor commands were identical in these two modes, visual stimuli processing and execution of efferent motor commands were not as strongly affected by the age in the subjects. The difference was likely due to afferent somatosensory signals and cognitive processing preparing the motor responses.

Deterioration of touch receptors and nervous transmission is ongoing process in peripheral nervous system [25, 31] which causes inacuity in the sense of touch [38]. The noisy and sometimes incongruent stimuli cues are integrated in the CNS to consistent percept. The human nervous systems changes over time to be more permissive for accuracy of integrated signals [33] causing elder people construct different precept of same stimuli from that young would [29, 13].

Immediate nature of the effect

The change in response time was present immediately after introduction of the plate and remained also after removing the plate. There was no time for motor or sensory learning, instead the response generation control have changed. The subjects were not described of the changed mechanical properties of the buttons. Instead, they were explained to press the buttons as before but with the plate between the fingers and buttons. Visual stimuli

remained the same. The conditions were same except for the plate which produced different sensory signals from the hands to the CNS.

We speculate that the intervention with the plate results in highly similar tactile and kinaesthetic afferent signals from the receptors of each of the hands. For elder subjects, the high similarity of the bimanual signals may lead to a different interpretation of the task when the different haptic sensations were integrated into perception in CNS [42]. Younger subjects with higher sensory acuity and better bimanual control were, however, not affected.

Conclusions

We presumed that a mechanical augmentation would influence the behaviors of subjects. The influence was observed in the mode of synchronous bilateral movement patterns of middle-aged subjects. The effect of the augmentation was observable even after the mechanism was removed. The persistence of the changed behavior is yet to be determined.

The specific bimanual synchronous movement pattern is associated with undeveloped and also with degenerated motor performance. However, because we did not observe adverse influences in the unilateral pattern, we consider the observed effect as an improvement in performance. The variety of applied bimanual behaviors is far more complex, and it would be valuable to explore if other modes of bimanual behaviors could be augmented with a similar mechanism.

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AUTHOR CONTRIBUTIONS MI Conceived and designed research, MI & NL Performed experiments, MI Analyzed data, MI & RB Interpreted results of experiments, MI Prepared figures, MI Drafted manuscript, All Authors Edited and revised manuscript, and All Authors Approved final version of manuscript.

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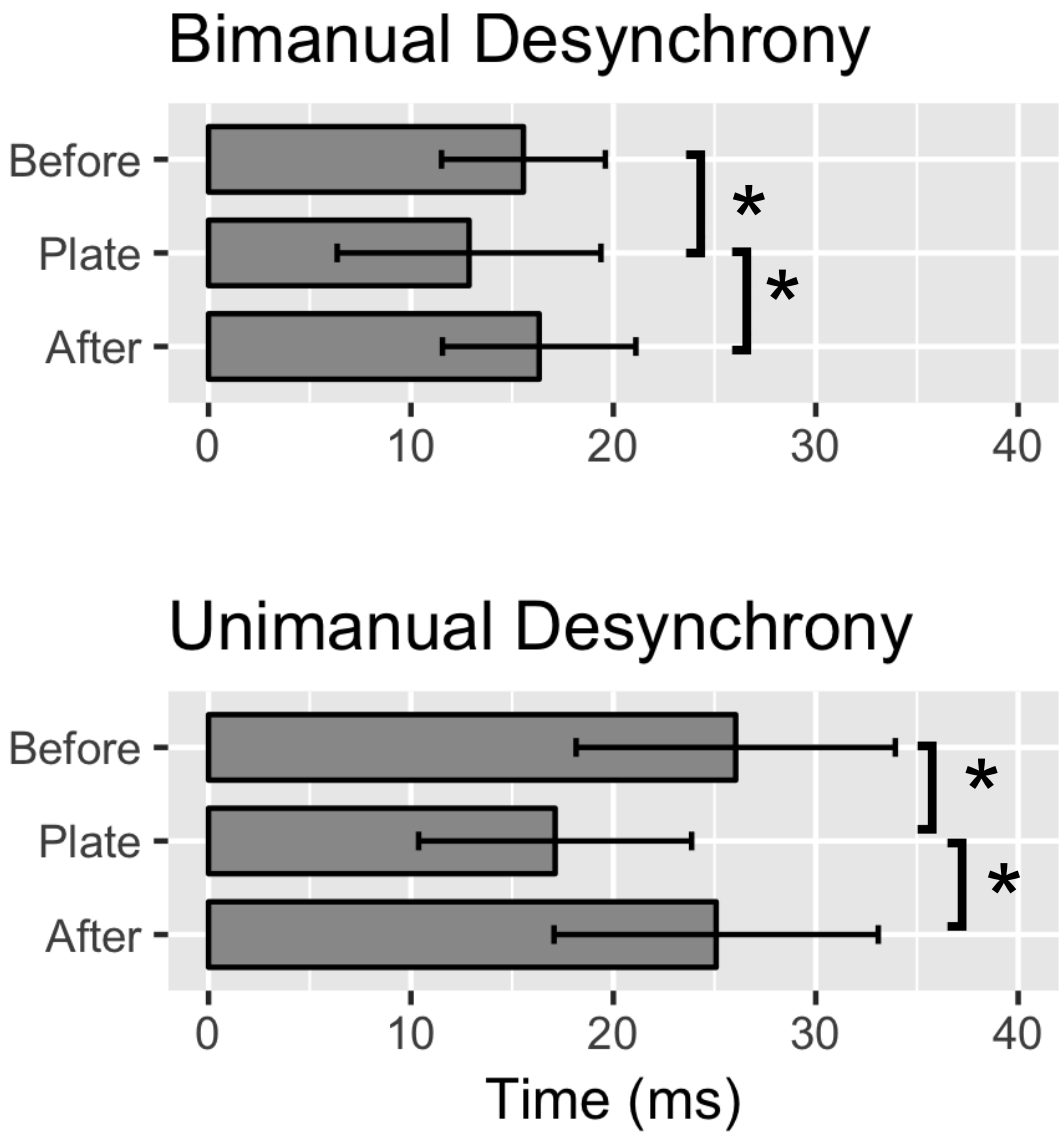

Figure 3: Desynchrony times in two-finger responses: The time difference between the presses of fingers was significantly reduced with the use of the plate. The significant differences between Plate and other conditions are marked with asterisk(*). The other differences are not statistically significant. The whiskers are drawn at ±SD

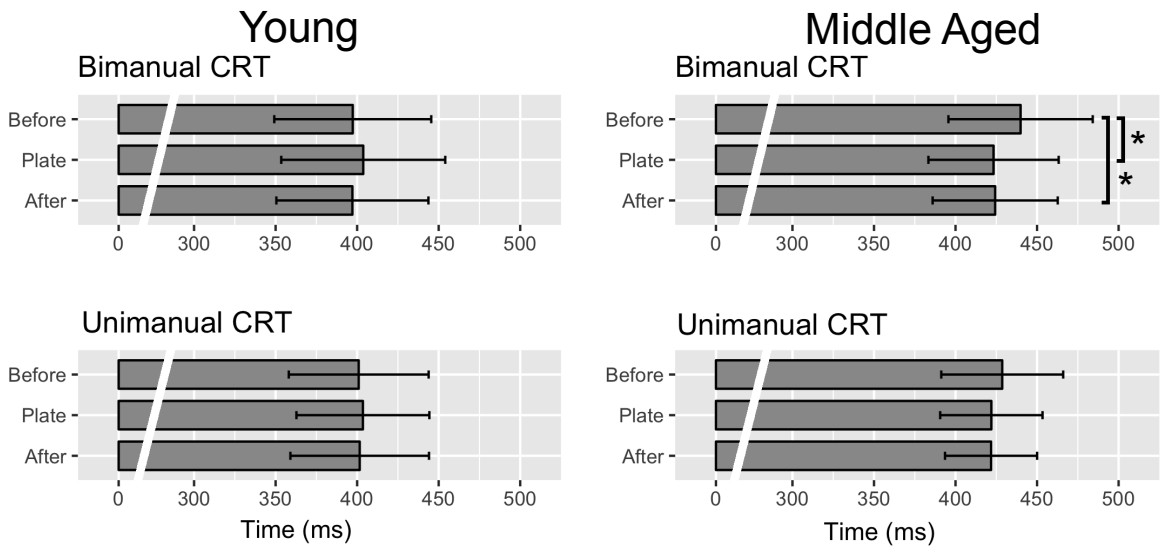

Figure 4: Bimanual and unimanual CRT tasks in age groups: $(20-39$ years) and Middle aged $(40-59)$. Significant changes in bimanual CRT were observed following the introduction of the plate. The significant differences are marked with asterisk(*). Other differences are not statistically significant. The whiskers are drawn at $\pm$SD

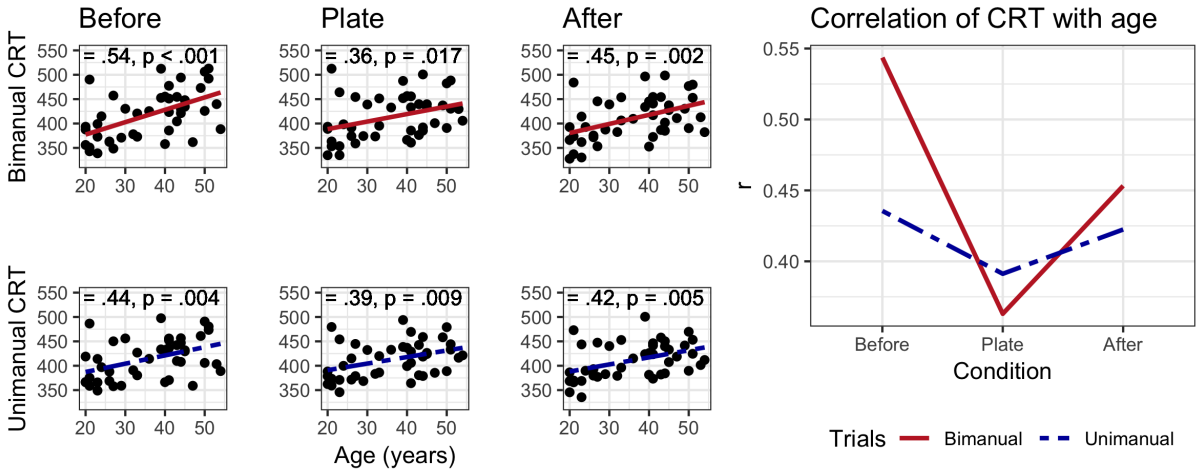

Figure 5: Correlation of CRT with age under each condition: The correlation of bimanual CRT with age is significantly reduced from Before condition to Plate condition. Conversely, the change in unimanual correlation with age is not significant. "r" represents Pearson's coefficient of correlation.