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Visuomotor adaptation in young adults with and without motor difficulties

Chi-Mei Lee

Visuomotor adaptation in young adults with and without motor difficulties

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Chi-Mei Lee

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Thesis Committee:

Jin Bo, PhD, Assistant Professor, Chair

Thomas A. Schmitt, PhD, Assistant Professor

Renee R. Lajiness-O’Neill, PhD, Associate Professor

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Abstract

Children with Developmental Coordination Disorders (DCD) have shown motor learning deficits in visuomotor adaptation tasks, and the failure of detecting errors seems to be the key that impedes motor learning. Recent studies suggested that presenting larger feedback improves the rate and extent of motor learning in healthy subjects and stroke patients. The present study recruited young adults with and without motor difficulties and aimed to examine their adaptability in visuomotor adaptation tasks with either regular (30° rotation) or enlarged (30° + double error) visual feedbacks. Results revealed that participants with lower motor ability showed less adaptability than those with higher motor ability in the regular feedback condition. However, they were able to reach a similar level of adaptability compared to the controls in the enlarged feedback condition. It can be argued that participants with motor difficulties can successfully compensate for their "noisy" visuomotor mapping by relying more on their feedback processes.

Key words: visuomotor adaptation, visuomotor coordination, motor difficulties, visual feedback, augmentation

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Chapter 1: Introduction and Background

Introduction

Many motor tasks require fine eye-hand coordination, including reaching, typing, writing, and other complicated movement. Skillful use of hands under visual guidance represents a major human achievement in the ability to interact with the environment. The acquisition processes for these motor skills, or motor skill learning, are defined as "…a set of processes associated with practice or experience leading to relatively permanent changes in the capability for responding" (Schmidt, Sherwood, & Walter, 1988).

Recent literature indicates that motor difficulties among children are associated with learning deficits, including autism (Gidley Larson & Mostofsky, 2008; Mostofsky, Goldberg, Landa, & Denckla, 2000), dyslexia (Goodgold-Edwards & Cermak, 1990; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003), Developmental Coordination Disorder (DCD; Bo, Bastian, Kagerer, Contreras-Vidal, & Clark, 2008; Kagerer, Bo, Contreras-Vidal, & Clark, 2004), and Attention-Deficit Hyperactivity Disorder (ADHD; Brook & Boaz, 2005; Seager & O'Brien, 2003). These children are normally at risk for many adverse outcomes, such as poor academic achievement (Brenner & Gillman, 1966; Gillberg & Kadesjo, 2003; Henderson, Barnett, & Henderson, 1994; Smyth, 1994; Tucha & Lange, 2004), socio-emotional difficulties (Chaix et al., 2007; Gillberg & Kadesjo, 2003; Hadders-Algra & Gramsbergen, 2003), long-term health problems (Cairney, Hay, Faught, & Hawes, 2005; Chaix et al., 2007; Faught, Hay, Cairney, & Flouris, 2005; Watemberg, Waiserberg, Zuk, & Lerman-Sagie, 2007), and low quality of life (Kennedy et al., 2007). The changes of symptoms and outcomes for adolescents and adults with motor difficulties, however, are not well documented. Therefore, more studies are warranted to enhance our understanding of motor learning and to develop appropriate interventions for those who suffer from motor deficits.

Understanding the developmental courses of motor skill acquisition is necessary to study important factors that influence people's motor learning. Researchers who study motor skill acquisition have classified motor learning into two broad domains: visuomotor adaptation and sequence learning (Doyon, Penhune, & Ungerleider, 2003; Willingham, 1998). Visuomotor adaptation is the capacity to modify coordinated movements to adjust to changes in a new environment, such as driving a different car or doing tasks in front of mirror; motor sequencing is the ability to integrate isolated movements into a complex, coherent action, such as playing piano or operating machines in particular ways (Doyon et al., 2003; Seidler, 2006; Willingham, 1998).

Previous studies suggested that children with motor difficulties showed less adaptbility than normal controls in visuomotor adaptation tasks (Kagerer, Contreras-Vidal, & Stelmach, 1997; Kagerer, Bo, Contreras-Vidal, & Clark, 2004; Kagerer, Contreras-Vidal, Bo, & Clark, 2006). Kagerer et al. (2004) suggested that the children with DCD were less affected by the feedback distortion and had less learning than the controls due to their less well-defined visuomotor mappings (Kagerer et al., 2004). A follow-up study examining different adaptation conditions (abrupt and gradual perturbation) revealed that the children with DCD could perform as well as the typically developing children when exposed to larger error signals in the abrupt visuomotor perturbation (Kagerer et al., 2006). These results suggested that visual feedbacks did play a differential role in the adaptation process of the children with DCD who were able to update their internal visuomotor mappings.

Based on previous studies (Kagerer et al., 2004; Kagerer et al., 2006), it seems that it is possible to facilitate motor learning in patients with coordination deficits based on different visual feedback. Recently, it has been reported that presenting enlarged visual feedback errors can improve the rate and extent of motor learning in healthy subjects (Wei, Bajaj, Scheidt, & Patton, 2005) and stroke patients (Patton, Stoykov, Kovic, & Mussa-Ivaldi, 2006; Sharp, Huang, & Patton, 2010). Unfortunately, little attention has been directed toward the learning deficits in populations with motor problems.

The current project focused on the visuomotor adaptation since the ability to adapt to the environment becomes vital in adulthood for maintaining activities of daily living and further indirectly impacts the mental health of individuals, families, and society (Zoia, Barnett, Wilson, & Hill, 2006). It is worth discussing the effect of visual feedback augmentation on patients with motor difficulties and its application on intervention.

Significance of the Study

The present study is one of the few studies focused on motor learning deficits in adulthood, and it is the first study examining the influence of error augmentation on participants with motor difficulties using the kinematic adaptation paradigm. The findings of the current study provided the preliminary information about visuomotor coordination in individuals with motor difficulties and in the normal population. It also offered a fundamental framework for developing intervention strategies to improve performance in individuals with motor difficulties.

Aims of the Proposed Study

While the impact of motor difficulties has been acknowledged as continuing into adulthood, the understanding of symptoms and intervention approaches was mainly from studies in children. Our knowledge of the pattern of presentation in adults with motor difficulties and the impacts it has on individuals' lives remains limited. In addition, how the amplitude of errors influences visuomotor adaptation in adults with motor difficulties is still unclear. The present study focused on young adults with and without motor difficulties and aimed to examine the hypothesis that young adults with motor difficulties can adapt better to changes in the computer adaptation tasks when visual feedback is enlarged.

The specific aims and hypotheses are described below:

Specific Aim 1: To examine whether participants with motor difficulties (total score of Adult Developmental Coordination Disorders/Dyspraxia Checklist [ADC] ≧ 70) were able to adapt to changes in computer adaptation tasks in different visual feedback conditions.

- Hypothesis 1-1: Adults with motor difficulties would show less adaptability (i.e. less adaptation with larger spatial errors) than controls in the regular visual feedback condition.
- Hypothesis 1-2: Adults with motor difficulties would show compatible adaptability with controls in the enlarged visual feedback condition.
- Hypothesis 1-3: Adults with motor difficulties would show stronger adaptability in the enlarged visual feedback condition than they do in the regular condition. The differences between conditions would not be found in the controls.

Specific Aim 2: To examine the relationship between motor ability (measure by ADC) and the adaptability in computer adaptation tasks.

- Hypothesis 2: Instead of group comparison, the ADC was treated as a regressor. The adaptability in the regular visual feedback condition would be strongly influenced by ADC scores while the adaptability in the enlarged visual feedback condition would not be affected. Overall, the degree of motor deficit severity would have a negative relationship with adaptability (i.e. participants endorsed higher ADC scores would show less adaptability with larger spatial errors).

Chapter 2: Review of Related Literature

In the literature, a number of terms have been used to describe patients with motor difficulties, such as Developmental Dyspraxia (Ayres, 1972), clumsiness (Henderson & Hall, 1982), physical awkwardness (Miyahara & Register, 2000), Clumsy Child Syndromes (Cratty, 1994; Illingworth, 1968; Wilson, 1974), perceptual-motor dysfunction and motor delay (Henderson et al., 1994), and Specific Developmental Disorder of Motor Function (WHO, 1992). The term Developmental Coordination Disorder (DCD) is used in the following review in accordance with the *Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition, Text Revision* (DSM-IV-TR) (APA, 2000).

In the following sections, a short overview of DCD in childhood and adulthood was provided first. In order to understand human movement, a stochastic optimized-submovement model proposed by Meyer and colleagues (1988) was introduced afterward. According to the model, the relationships between error distortion and performance were discussed at the end.

Developmental Coordination Disorder

Developmental Coordination Disorder (DCD), a chronic and usually permanent condition, is characterized as having motor difficulties in gross and/or fine motor coordination and in the learning of new motor skills (Barnhart, Davenport, Epps, & Nordquist, 2003; Cantell, Smyth, & Ahonen, 2003). This idiopathic disorder is diagnosed in children who fail to acquire adequate motor skills comparable to their chronological age for no medical reason.

According to the DSM-IV-TR, the criteria for diagnosis of DCD include (a) performance in daily activities that require motor coordination is substantially below that expected given the person's chronological age and measured intelligence; (b) the motor disturbance significantly interferes with academic achievement or activities of daily living; and (c) the motor disturbance is not due to a general medical condition (e.g., cerebral palsy, hemiplegia, or muscular dystrophy) and does not meet the criteria for a Pervasive Developmental Disorder (APA, 2000). Up to 6% of American school children are thought to be affected by DCD (APA, 1994, 2000; Polatajko et al., 1995; Wilson & McKenzie, 1998). The marked impairments of motor abilities have significant, negative impact on activities of daily living, such as dressing, eating, and/or handwriting, which may result in lowered self-esteem (Poulsen, Ziviani, & Cuskelly, 2007), greater social isolation (Dewey, Kaplan, Crawford, & Wilson, 2002), and poor academic achievements (Kirby & Sugden, 2010).

While an increasing number of studies have focused on understanding the children with DCD, few studies have been reported on adolescents and adults with motor difficulties. The earliest study on the prognosis of "clumsy children" revealed a favorable outcome in participants with mild and moderate degrees of clumsiness (Knuckey & Gubbay, 1983). Only the most severely affected subjects failed to grow out of their coordination difficulties when they were followed up at their late adolescent or early adulthood (16-20 years old; Knuckey & Gubbay, 1983). However, there might be confounded factors on the task difficulties. In Knuckey and Gubbay's (1983) report, the participants received a subset of the same tests they had used 10 years ago, which might not be the age-appropriate tasks.

A longitudinal study of children with DCD demonstrated variability of outcomes (Cantell, Smyth, & Ahonen, 1994). Cantell et al. (1994) re-examined three groups of individuals at age 15. One group had significant motor difficulties in their childhood. The second group had minor motor problems, and the third was a control group. Based on pre-existing child assessment tools, Cantell et al. (1994) revised some of the tasks based on developmental concerns. The results showed that 46% of the members with significant motor difficulties continued to have problems on motor and perceptual tasks, whereas the intermediate group appeared to be more like controls (Cantell et al., 1994).

The only longitudinal study regarding young adults with motor difficulties was conducted in Sweden by Gillberg and colleagues (Gillberg & Gillberg, 1983; Gillberg, Gillberg, & Groth, 1989; Hellgren, Gillberg, Bagenholm, & Gillberg, 1994; Rasmussen & Gillberg, 2000). The participants were diagnosed at 7 years of age with DCD and ADHD in a community-based study and were reviewed at 22 years of age. The results suggest that 59% of the subjects who had DCD with comorbid ADHD had poorer outcomes compared to 13% in the comparison controls. The participants with DCD and ADHD were also at high risk to present antisocial personality disorder, alcohol abuse, criminal offending, reading disorders, and low educational level. The combination of DCD and ADHD seems to be a predictor of a gloomy prognosis (Rasmussen & Gillberg, 2000).

Evidence shows that 30-87% of children with DCD will not “grow out” of their difficulties (Cantell et al., 1994; Cousins & Smyth, 2003; Hellgren et al., 1994; Kirby & Sugden, 2010). There might be a number of contributory factors to explain why these figures vary so greatly, such as selection criteria, severity of symptoms, and comorbidities. With no doubt, however, the motor difficulties continue to impact these children to their adulthood. Adults with DCD demonstrate poor performance in many visuomotor coordination tasks, including manual dexterity, handwriting, and sequencing (Cousins & Smyth, 2003). Common associated difficulties included poor executive functioning (time management, organization, planning, problem solving, etc.), low self-esteem, loneliness, and difficulties in making and maintaining friendships (Kirby, Edwards, & Sugden, 2011; Kirby & Sugden, 2010). Understanding these individuals' motor abilities and symptoms change in their adulthood may help in developing appropriate interventions.

Motor Adaptation and DCD

Previous visuomotor studies have been done with children in order to improve fine motor skills (Connolly, 1970; Kay, 1970; Platzer, 1976). These early studies in the field revealed the progression of movement proficiency during years of practice. Most intervention studies showed positive effects over no-intervention controls with no significant advantage for widely differing approaches (Sugden, 2007; Sugden & Chambers, 1998). These patterns suggest that there may be other factors along with pure motor practice that result in the observed changes.

In order to study these factors that may influence people's motor skills, understanding the developmental courses of motor skills is necessary. Researchers who study skill acquisition have classified motor learning into two broad domains: visuomotor adaptation and sequence learning (Doyon, Penhune, & Ungerleider, 2003; Willingham, 1998). Visuomotor adaptation is the capacity to modify coordinated movements to adjust to changes in a new environment, such as driving a different car or doing tasks in front of mirror; motor sequencing is the ability to integrate isolated movements into a complex, coherent action, such as playing piano or operating machines in particular ways (Doyon et al., 2003; Seidler, 2006; Willingham, 1998). The current project focused on the visuomotor adaptation since the ability to adapt to the environment becomes vital in adulthood for maintaining activities of daily living and further indirectly impacts the mental health of individuals, families, and society (Zoia, Barnett, Wilson, & Hill, 2006).

According to a stochastic optimized-submovement model proposed by Meyer and colleagues (1988), feed-forward and feedback mechanisms are two principal control proceedings of movements (Meyer, Abrams, Kornblum, Wright, & Smith, 1988). An aimed movement toward a specified target region involves two subcomponents of movement: (a) the initial ballistic phase, a primary submovement based on movement planning that guides the movement toward the target (feed-forward mechanism), and (b) the corrective phase, an optimal secondary submovement based on feedback where adjustments are made (feedback mechanism). Supplementary motor area (SMA), premotor cortex (PMC), prefrontal cortex, and basal ganglia have been suggested to be involved in the planning (feed-forward mechanism) of movements; cerebellum, anterior cingulated cortex, and parietal cortex have been suggested to be involved in the control (feedback mechanism) of movements. This conceptual framework provides insights into principles of motor performance, and it links physical action to sensation, perception, and cognition (Meyer et al., 1988).

The planning and execution of hand movements in relation to visual targets requires the visual signals (i.e., information about the position of the hand and the location of the target). The visual signals are transformed into messages that activate the appropriate muscles in order for the hand to reach the target or perform actions. This visual-motor coordination can be conceptualized as an internal model of the relationship between visual space and motor space (Wolpert & Ghahramani, 2000; Wolpert, Ghahramani, & Jordan, 1995). The internal representation needs to be adaptive, across the lifespan to compensate to limb growth and to allow for learning how to use new tools, or adapt to the presence of visually distorted environments (Contreras-Vidal, Bo, Boudreau, & Clark, 2005; Kagerer, Contreras-Vidal, & Stelmach, 1997). Through the adaptive process, the internal visuomotor mapping can be updated over time.

Previous studies on children with DCD suggest that poor visuomotor mapping underlies their motor learning deficits (Kagerer et al., 2004; Kagerer et al., 1997). Kagerer et al. (2004) reported a study where children with and without DCD adapted to a novel visuomotor relationship with a 45° visual feedback rotation. The results showed that the children with DCD were less affected by the feedback distortion and had less learning than the controls. Their results suggested children with DCD had less well-defined visuomotor mapping (Kagerer et al., 2004). In a follow-up study, Kagerer et al. (2006) examined different adaptation conditions (abrupt and gradual perturbation) in children with DCD and typically developing children using a similar center-out drawing task. The children with DCD did not appear to be able to utilize the small error signals provided during the gradual perturbation, but they could perform as well as the typically developing children when exposed to larger error signals in the abrupt visuomotor perturbation. These results suggested that adaptation conditions did play a differential role in the adaptation process of the children with DCD who were able to update their internal model under conditions of an abrupt visuomotor distortion (Kagerer et al., 2006).

Based on previous studies (Kagerer et al., 2004; Kagerer et al., 2006), it seems that it is possible to facilitate motor learning in patients with coordination deficits based on different visual feedback. Recently, it has been reported that presenting enlarged visual feedback errors (e.g. the cursor is really off the correct direction) can improve the rate and extent of motor learning in healthy subjects (Wei et al., 2005) and stroke patients (Patton et al., 2010). Unfortunately, little attention has been directed toward the learning deficits in populations with motor problems. It is worth discussing the effect of visual feedback augmentation on patients with motor difficulties and its application on intervention.

Visual Feedback Augmentation

The role of error feedback in motor adaptation has been emphasized in many theoretical approaches. It has been reported that presenting larger visual feedback in adaptation tasks can improve the rate and extent of motor learning (Patton, Stoykov, et al., 2006; Wei et al., 2005). Many models and artificial learning systems suggest that error drives learning so that one can learn more quickly if error is larger (Rumelhart, Hinton, & Williams, 1986). Such error-driven learning processes are believed to be central to adaptation and the acquisition of skill in human movement (Gomi & Kawato, 1993). Also, larger errors are likely to heighten motivation to learn by making the consequence of even small errors seem large. It makes errors more noticeable to the senses and hence may trigger responses. In other words, intensifying error can lead to larger signal-to-noise ratios for sensory feedback and self-evaluation (Wei et al., 2005).

In one of a series of investigations, Patton et al. (2006) found that using robotic devices can facilitate adaptive training in hemiparetic stroke patients. In the study, stroke survivors experienced training forces that were either amplified or reduced their hand path errors. They found that subjects could adapt to the visual rotation just as normal controls. Significant trajectory improvements occurred only when the training forces magnified the original errors and not when the training forces reduced the errors or the errors were absent. The finding suggests that error-enhancing training may be an effective way to promote functional motor recovery for brain injured individuals (Patton et al., 2006).

Similar findings were obtained by Sharp et al. (2010) in a non-clinical sample. They recruited 10 healthy subjects to perform targeted reaching in a virtual reality environment, where the transformation of the hand position matrix was a full reversal (180° rotations). The findings show that subjects who received doubled error augmentation were able to reach their desired target more quickly and accurately than their baseline performance. These data further support the theory that feedback enhancement may promote more complete adaptation/learning than regular training (Sharp et al., 2010).

While the data presented thus far suggest that error augmentation during training can facilitate motor learning, several questions remain unanswered. A central issue is the magnitude of the error-augmentation condition that is optimal for improving visuomotor skills. To investigate this issue, Wei et al. (2005) recruited sixteen neurologically normal adults and asked them to reach with their unseen arm to visual targets surrounding a central starting location. For one group of subjects, deviations from the ideal hand movement (error) were amplified with a gain of 2; another group was provided visual feedback with a gain of 3.1. The results showed that the performance of subjects in the gain 3.1 group no better than the controls (regular feedback) and worse than the gain 2 group. One possible explanation is that larger gain may have decreased the relative stability of the adaptation process beyond which the subjects were comfortable, thus causing them to down-regulate their internal feedback gain so that the overall gain approached “normal.” They suggested that the optimal gain is between 1 and 3.1 for visuomotor adaptation tasks (Patton & Huang, 2012; Wei et al., 2005). Sharp et al.’s study has also suggested that visual error augmentation with a gain of 2 is the optimal distortion to facilitate improvement in performance (Sharp et al., 2010). Therefore, a gain of 2 is used in this study for testing the effect of error augmentation.

Chapter 3: Research Design and Methodology

Participants

Twenty-seven adults (10 males, 17 female), aged from 18 to 34, were recruited from Eastern Michigan University and the nearby community via in-class announcements, the SONA system, and flyers. Right-handers were predominant in this sample; only five participants were categorized as left-handed and one as ambidextrous based on their report on the Edinburgh Handedness Inventory (Oldfield, 1971). All participants' intelligence estimated by Shipley Institute of Living Scale (Zachary 2006) was greater than 80.

Based on the self-reported developmental and medical history, none of the participants reported having DSM-IV-TR diagnosis of schizophrenia, schizoaffective disorder, delusional disorder, other psychotic disorder, organic psychosis, schizotypal personality disorder, and bipolar affective disorder. No participants had a diagnosis of pervasive developmental disorder or mental retardation. Five participants reported having history of depression and/or anxiety, and one participant reported having substance use problems, but none of them were currently suffering from depression episode, having panic attacks, or experiencing substance intoxication or withdrawal at the time of evaluation. None of the participants reported having any acquired or neurological disorders that might account for motor difficulties, having visual or hearing impairments, or having a motor disability, which may influence the process of neuropsychological assessment. Four participants reported having a diagnosis of Attention Deficit/Hyperactivity Disorder (ADHD; 3 were diagnosed before 7 years of age and 1 received diagnosis at age of 25), and one of them was currently prescribed medication for

ADHD. No changes to participants' medication prior to and during the assessment.

Based on the Adult Developmental Coordination Disorders/Dyspraxia Checklist (ADC; Kirby et al., 2010), four out of 27 participants endorsed a total score higher than 90, which suggested possible diagnosis of Developmental Coordination Disorder (DCD). Two participants endorsed scores between 80 and 90, which suggested that they might at high risk of having DCD. Five participants endorsed scores between 70 and 80, which suggested that the poor motor ability influences their daily life and causes slight impairment in functioning. For the purposes of this project, the participants who scored equal to or higher than 70 in ADC were considered to have motor difficulties. The ADC score distribution among the participants is shown in Figure 1.

Procedures

This research was approved by the Institutional Review Board of Eastern Michigan University (EMU) prior to its implementation. A face-to-face explanation of the purpose and procedure of this study and reassurance of confidentiality were performed, and the written informed consent from young adults was obtained before the assessment of subjects.

All the participants completed the visuomotor adaption tasks to evaluate their motor adaptability in two conditions: enlarged and regular feedback settings. The order of conditions was counterbalanced within each group. In order to control for the learning carry-over effects from the first visuomotor adaptation conditions, the two settings were tested at different testing dates. The second testing was performed 10 days (± 3 days) after the first one.

After completing the visuomotor adaptation tasks, participants were administered a variety of questionnaires and the measures regarding motor ability, psychopathology, and neuropsychological functions. The Shipley Institute of Living Scale for intelligence was completed on the second testing date after the visuomotor adaptation task. All the tasks and assessments were administered at the cognitive neuroscience lab at Eastern Michigan University.

Measurement

Visuomotor adaptation tasks. The visuomotor adaptation tasks written in PRESENTATION were administrated to all the subjects. Participants were seated in front of a table facing a computer monitor, with their dominant hand holding a joystick. The joystick was used to collect the digitized data of the participants' hand movements in x/y coordinates at a 60Hz sampling rate. Visual feedback of the hand movements (displayed as a computer cursor) was provided in real-time on the computer monitor with two different experimental conditions, enlarged and regular visual feedback.

Participants were asked to move a cursor between home positions and target positions displayed on the computer screen (Figure 2). The home position was displayed on the monitor as a picture of a yellow smiling face located at the center of the screen. The target position was one of eight green smiling face pictures (diameter of the picture: 1 cm) appearing randomly in one of eight locations (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) around the home position (distance from home position to target: 10 cm). The home position was visible throughout the duration of the testing session. The target appeared as soon as the cursor stayed in the home position motionless for 1 second, and disappeared as soon as the cursor entered the target picture. Participants were instructed to move the cursor as fast and as straight as possible from the home position to the target when ready.

The task consisted of five phases: (A) baseline phase: 24 trials (3 trials per angle, 3 blocks) with normal visual feedback of the hand movements; (B) first exposure phase: 32 trials (4 trials per angle, 4 blocks) with the visual feedback of the hand movement rotated 30° anticlockwise (the hand movement and visual effect on the screen do not match); (C) second exposure phase: 48 trials (6 trials per angle, 6 blocks) with the visual feedback of the hand movement rotated 30° anticlockwise in the regular condition, or with the enlarged visual feedback which doubled the discrepancy between hand movement and ideal movement in the enlarged condition; (D) third exposure phase: 32 trials (4 trials per angle, 4 blocks) with the visual feedback of the hand movement back to 30° rotation; (E) post-exposure phase: 8 trials (1 trial per angle, 1 block) with normal visual feedback of the hand movements to test for after-effects.

There were 6 catch trials in three exposure phases in order to track participants' learning curve progress. Each catch trial was introduced after 16 exposure trials; therefore, there are two catch trials in the first exposure phase (B), three catch trials in the second exposure phase (C), and one catch trial in the third exposure phase (D). Two different experimental conditions were tested during the second exposure phase. The feedback error was either enlarged (doubled error) or regular (30° rotation). All participants performed both conditions with the order of conditions being counterbalanced.

Developmental and medical history (Polanczyk et al., 2003). A 23-item self-report questionnaire revised from a semi-structured family history of health, behavior, and mental disorders interview (Polanczyk et al., 2003) was administered to the participants. The interview was originally developed for a family study of affective spectrum disorders at the NIMH Section of Developmental Genetic Epidemiology. Basic demographic information, developmental milestones, significant medical history (hospitalization, surgery, and head injury involving unconsciousness), and motor-related neurological disorders (including seizure, ADHD, Pervasive Developmental Disorders, and learning disabilities) were collected from the questionnaire.

Self-report measurements.

The Adult Developmental Coordination Disorders/Dyspraxia Checklist (ADC, Kirby et al., 2010). The ADC is the first adult screening tool for Developmental Coordination Disorder (DCD), which is designed to assess the motor difficulties for adults over 16 years of age (Kirby, Edwards, Sugden, & Rosenblum, 2010). The 40-item measurement is divided into three sections: childhood difficulties (10 items), individual's perception of current difficulties (10 items), and current difficulties as reflected upon by others (20 items). The 4-point rating scale (0 = *never*, 1 = *sometimes*, 2 = *frequently*, and 3 = *always*) is used to reflect the degree of motor deficit severity. There are no reverse scored items. Three scores - childhood functioning (10 items of childhood difficulties), current functioning (30 items of current difficulties), and total score (sum of the three sections) - are computed. The score of childhood functioning can range from 0 to 30, with higher values reflecting greater motor deficits in childhood. Scores of 18 and higher indicate "probable" DCD in childhood (Kirby et al., 2010). The score of current functioning can range from 0 to 90, with higher values reflecting greater motor deficits currently. The total score of all items can range from 0 to 120, with 90 as a suggested cutoff point. Scores of 90 and above indicate "probable" DCD, scores of 80 to 90 suggest at high risk of having DCD, and scores of 70 and above indicate having motor difficulties.

Kirby et al. (2010) reported that the ADC had satisfactory internal reliability (childhood difficulties $\alpha = .91$, individual's perception of current difficulties $\alpha = .87$, and current difficulties reflected upon by others $\alpha = .90$). The construct validity of ADC was examined by comparing college students with and without DCD on ADC scores. Significant differences were found between the groups for the mean total score of the ADC (t = 11.85, p < .001). Concurrent validity was examined by comparing the ADC subscales with the Handwriting Proficiency Screening Questionnaire (HPSQ). A significant moderate correlation was found between the ADC's subscales and HPSQ mean final scores (childhood difficulties γ = .68, individual's perception of current difficulties γ = .75, and current difficulties reflected upon by others γ = .71). Regarding discriminant validity, 91% of the control group and 84% of the DCD group were correctly classified in the previous study, which suggests that the ADC is a suitable screening tool for adult DCD (Kirby et al., 2010).

The Adult Self-Report Inventory-4 (ASRI, Gadow et al., 2002). The ASRI, a 135-item self report or interview scale, is derived from the Youth Self-Report Inventory (Gadow et al., 2002) for the purpose of making the DSM-IV referenced psychiatric diagnosis in adults. Symptom categories include ADHD, Oppositional Defiant Disorder (ODD), Conduct Disorder (CD), Eating Disorders, Dissociative Disorder, Mood Disorders, Anxiety Disorders, Schizophrenia, Somatization Disorder, and Substance Use Disorders. The 4-point rating scale (0 = *never*, 1 = *sometimes*, 2 = *often*, and 3 = *very often*) is used to reflect the degree of the symptoms. There are two scoring procedures: symptom count (number of DSM-IV-specified symptoms) and symptom severity (dimensional). The ASRI-4 scores have satisfactory reliability and convergent and discriminant validity with corresponding scales of other recognized measures of psychopathology, and the scores differentiate clinic from non-clinic samples (Gadow, Sprafkin, & Weiss, 2004). The ASRI-4 was used to assess participants' psychopathology and rule out unsuited participants.

Neuropsychological tests.

The Shipley Institute of Living Scale (Zachary 2006). The *Shipley Institute of Living Scale* is designed to assess general intellectual functioning in adolescents and adults (ages 14 and older) and help in detecting cognitive impairment in individuals with normal intelligence. The scale consists of two subtests: a 40-item vocabulary test and a 20-item abstract thinking test. The vocabulary subtest uses a multiple-choice format. Individuals are asked to choose which of four possible words "means the same or nearly the same" as a specified target word. The abstraction subtest uses a completion format. Individuals are asked to fill in the numbers or letters that best complete the logical sequence. The total administration time for the test is 20 minutes, 10 minutes for each subtest (Zachary, 2006).

There are six major summary scores: (a) Vocabulary score; (b) Abstraction score; (c) Total score, which combines vocabulary and abstraction scores; (d) Conceptual Quotient (CQ), an objective measure of intellectual impairment (> 90, normal; 70 ~ 90, suspicious; < 70, probably pathological); (e) Abstraction Quotient (AQ), an index of impairment based on a regression equation that predicts Abstraction scores for a given individual from the individual's Vocabulary score, age, and educational level (> 90, normal; 70 ~ 90, suspicious; < 70, probably pathological); and (f) estimated Full Scale IQ score based on the Wechsler Adult Intelligence Scale-Revised (WAIS-R).

The *Shipley Institute of Living Scale* is thought to have good temporal stability and internal consistency. The test-retest reliability coefficients range from .60 to .82 for total score with intervals from 2 to 16 weeks (Mason & Ganzler, 1964; Stone, 1965; Tamkin & Jacobsen, 1987). Internal consistency for the total score was found to be .92. Several studies also suggest that the *Shipley* has good validity. These studies show correlation coefficients ranging from .49 for the Slosson Intelligence test to .78 for the Army General Classification Test with a median of .69 (Zachary, 2006). These generally high correlations with other tests designed to measure intellectual ability and achievement provide additional evidence of the construct validity of the *Shipley* in its use as a brief estimator of general intelligence. For the proposed study, the *Shipley* served as a screening tool to rule out participants whose IQ are lower than 80.

Data Analysis

All neuropsycological and self-reported data collected by this study were entered, coded, and double-checked for errors and violations of assumptions. All of the hard copies were kept for data checking. Subsequently, the entered data were transferred to the SPSS software vision 18.0 (SPSS Inc., Chicago, III) and SAS 9.1 (SAS Institute Inc., Cary, NC, USA) to perform more sophisticated range checking.

The analyses of the off-line data collected by visuomotor adaptation tasks were performed in MATLAB. In order to reduce noise in the data, the velocity time series was subjected to a dual-pass 8^{th}-order Butterworth filter with a cutoff frequency of 10Hz. Customized MATLAB scripts searched the velocity time series and marked the starting points for each movement when the velocity exceeds 20% of the peak velocity. In cases where the algorithm failed to mark the onset, the experimenter manually adjusted the markers. After all of the movements had been verified, the dependent variables were calculated.

From the time series obtained, the following dependent variables were retrieved in the visuomotor adaptation tasks: (a) directional error (DE, in degrees) was defined as the directional deviation of the actual movement direction from the ideal movement direction at the peak of the tangential velocity profile (not likely to be under the influence of feedback processes); (b) movement total distance (DIST, in millimeters) was defined as the total movement length traveled by the joystick for each trial; (c) movement time (MT, in milliseconds) was defined as the time moving from the home position to the target position; (d) reaction time (RT, in milliseconds) was defined as the time moving from the starting point to the peak velocity time point; and (e) root mean square error (RMSE, in millimeters) was defined as the average point-to point spatial deviation of the actual movement trajectory from the ideal vector between home and target position (Contreras-Vidal, 2006; Contreras-Vidal et al., 2005).

Three methods were used in the present study to assess adaptability (learning effect) based on the above mentioned dependant variables.

Method 1: The changes of means across blocks in the three exposure phases and post-exposure phase were one way to estimate participants' learning. The first method assessed the differences of block means between exposure, post-exposure phases, and the baseline on all dependant variables.

Method 2: The second method checked the performance of six catch trials in the three exposure phases. Participants' performance on each catch trial was compared with the baseline.

Method 3: The third method compared the after-effects. To assess after-effects, the mean of the first three post-exposure trials was calculated for each variable and then compared to a mean of the third block in the baseline. The mean of the first three post-exposure trials was also compared to a mean of the last learning block in the third exposure phase to assess individual learning effect.

The following statistical analyses have been used for each aim and hypothesis:

Specific Aim 1: To examine whether participants with motor difficulties (ADC ≧

70) were able to adapt to changes in computer adaptation tasks during different visual feedback conditions.

To assess general differences between participants with motor difficulties and normal developed adults, a score of 70 on ADC was used as cutoff point in this study. Demographic homogeneity of the two groups (motor difficulties and controls) was assessed using chi-square tests or Fisher exact test for discrete variables. Independent-samples *t*-test on the continuous variables, such as sum or mean scores of motor ability, symptomatological items, and neuropsychological measures, were used to compare the differences between groups.

Hypothesis 1-1: Adults with motor difficulties would show less adaptability (i.e. less adaptation with larger spatial errors) than controls in the regular feedback condition.

Within regular condition, mixed model repeated-measures ANOVAs with groups (motor difficulties vs. controls) as a between-subjects factor and block as a within-subjects factor were used for method 1. The 112 trials in three exposure phases were divided into 14 blocks of 8 trials (4 blocks in the first exposure phase, 6 blocks in the second, and 4 blocks in the third), and the mean differences between each block and baseline were calculated. The Bonferroni method was used to adjust p values for the comparisons among the groups, blocks, and their interactions in the post hoc analysis. For method 2, six catch trials were treated as a within-subjects factor for the repeated-measures ANOVA analysis. For method 3, independent *t*-tests were used to compare the after-effect differences between groups with motor difficulties and the controls.

Hypothesis 1-2: Adults with motor difficulties would show similar adaptability in the enlarged visual feedback condition to controls.

The statistical models for the repeated-measures ANOVAs were the same as those for hypothesis 1-1, except that the data were for the enlarged condition.

Hypothesis 1-3: Adults with motor difficulties would show stronger adaptability in the enlarged visual feedback condition than they do in the regular condition. The differences between feedback conditions would not be found in the controls.

Three-way mixed model repeated-measures ANOVAs were performed with the group (motor difficulties vs. controls) as a between-subject factor, and the condition (regular vs. enlarged) and blocks (14 exposure blocks) as the within-subjects factors for method 1. The Bonferroni method was used to adjust p values for the comparisons among the groups, conditions, blocks, and their interactions in the post hoc analysis. For method 2, six catch trials were treated as a within-subjects factor for the 3-way ANOVA analysis. For method 3, two-way mixed model repeated-measures ANOVAs were performed with the group (motor difficulties vs. controls) as a between-subject factor and the condition (regular vs. enlarged) as a within-subject factor on after-effects.

Specific Aim 2: To examine the relationship between motor ability (measured by ADC) and the adaptability in different visual feedback conditions.

Hypothesis 2: Instead of group comparison, the ADC was treated as a regressor. The adaptability in the regular condition would be strongly influenced by ADC scores while the adaptability in the enlarged condition would not be affected by ADC scores. Overall, the degree of motor deficit severity would have a negative relationship with adaptability (i.e. participants endorsed higher ADC scores would show less adaptation with larger spatial errors).

Since it could be argued that ADC cutoff value of 70 was a little arbitrary, the current study used a regression analysis as an alternative approach to examine the relationship between motor ability and adaptability. Here, instead of group comparison, a mixed model linear regression analysis was performed on all the dependant variables, with ADC total score as a continuous variable (i.e. regressor) in the models. The conditions (regular vs. enlarged), and blocks (14 exposure blocks) were treated as the within-subjects factors for method 1. The catch trials were treated as the within-subjects factors for method 2. The after-effects were measured in method 3.

Chapter 4: Results

All participants were able to successfully complete the adaptation tasks and neuropsychological assessments within 3 hours (about 1.5 hours in two testing days). Visual inspections on the movement trajectories showed similar general patterns during the adaptation tasks. At the baseline, the movement paths were relatively straight from the home position to the target in both conditions. As the visual feedback rotation was introduced in exposure phase, participants began to ”fall short” of the target vector, which resulted in curved (spiral-shape) movement paths. Upon return to normal visual feedback in the post-exposure phase, the curvature of the movement paths mirrored that of the paths during early exposure trials, indicating after-effects.

Specific Aim 1: Group Difference between Participants with Motor Difficulties and Controls

Using ADC score equal to or above 70 as a cutoff point, participants were separated into two groups: 11 participants (5 males, 6 females), with a mean ± SD age of 21.91±2.85 years, were categorized into motor difficulties group; 16 participants (5 males, 11 females, age = 24.18±4.11 years) were grouped into controls. The ADHD symptoms measured by ASRS were significantly higher in participants with motor difficulties (Inattention: $F = 12.69$, $p = 0.002$; Hyperactivity/Impulsivity: $F = 12.67$, $p = 0.002$). Participants in two groups have similar level of intelligence measured by the *Shipley Institute of Living Scale* ($p = 0.872$). There were no differences in gender ($p = 0.453$), current ages ($p = 0.126$), education years ($p = 0.072$), race ($p = 0.410$), and handedness ($p = 0.970$) between motor difficulties and control groups.

Hypothesis 1-1: Adults with motor difficulties would show less adaptability than controls *in the regular feedback condition.*

In the regular condition, there was a significant main effect for blocks on all variables (all p <.01) in the exposure phases, suggesting the abilities of motor planning and motor control were improved across the 14 blocks of exposure for all participants (Figure 3). There were significant interactions (group*block) for MT (p = 0.017), and RMSE (p = 0.006). The post hoc analysis (Bonferroni adjusted) of the group x block interaction revealed that the controls had greater improvement on RMSE from block 1 to the rest of the blocks (blocks 2-14, all p < .01), from block 2 to blocks 8, 11, and 14 (all p < .01), and from block 3 to blocks 8 and 14 (both p < .01) compared to the group with motor difficulties. Interestingly, the group x block interaction on MT showed that the participants with motor difficulties had significantly improved their movement speed from block 1 to blocks 8, 11, and 14 (all p < .01), and from block 2 to blocks 8 and 14 (both p < .01) compared to the controls (Figure 3). These results revealed that, although participants with motor difficulties tried to move fast during learning, their movement spatial variability were not improved as fast as the controls during the exposure conditions.

Results from the performance of six catch trials showed significant main effect for group in DE (F = 6.52, p = 0.017). The outcome implied that in the regular condition, participants with motor difficulties made less change of directional errors between the catch trials and the previous learning trails, suggesting less adaptation across the exposure phase for the motor difficulties group compared to the controls. The group x trial interaction on RMSE was significant (p = 0.057).

Independent *t*-tests on after-effects (post-exposure - baseline) for each group were first performed to examine whether there was positive learning within groups. There were significant results for controls (in all dependent variables, *p* range from <.001 to 0.009) and for the motor difficulties group (in all dependent variables except for RT, *p* range from 0.001 to 0.068). The findings suggested that both groups displayed positive learning in the regular setting. Lack of significance on RT for the group with motor difficulties (*p* = 0.159) suggested no after-effect on movement planning.

Group comparisons of the mean of the first three post-exposure trials with the mean of the last learning block were further performed. Significant group difference was found in RT (F = 12.25, *p* = 0.002). Similar results were found when compareing the mean of post-exposure trials with the baseline. There was a significant group difference in RT (F = 9.58, *p* = 0.005). While the controls had significant after-effects on motor planning, the participants with motor difficulties did not show positive after-effect, suggesting no learning from the planning perspective (Figure 6).

Hypothesis 1-2: Adults with motor difficulties would show similar adaptability in the enlarged visual feedback condition to controls.

In the enlarged condition, there was a significant main effect for block (all variables *p* <.001) in the exposure phases, suggesting improvement across the fourteen blocks of exposure for all variables among all participants (Figure 4). Compared to controls, participants with motor difficulties spent less time planning their movement, supported by a significant main effect for group in RT (F = 3.64, *p* = 0.068). Significant group x block interaction on MT (*p* = 0.027) revealed larger movement speed changes from block 4 (i.e. the last block in the first exposure phase) to block 5 (i.e. the first block in the second exposure phase – enlarged error), from block 5 and 6 (i.e., first 2 blocks in the second exposure phase – enlarged error) to blocks 11 to 14 (i.e., all the blocks in the third exposure phase: 30-degree rotation without enlarged error feedback, all *p* < 0.01) for the group with motor difficulties compared to the controls. The group x block interaction on RMSE (*p* = 0.016) showed that the participants in the motor difficulties group decreased their spatial variability more than the controls from blocks 1 to blocks 11-14 and from block 2 to block 9 (all $p < 0.01$). The controls had significant improvement on RMSE from block 2 to blocks 11 and 13 and from block 5 to blocks 11-13 (all $p < 0.01$, Figure 4). These results generally implied that besides the overall improvements on spatial variability across the entire exposure phases (from the 1st to the 3rd exposure phases), participants with motor difficulties were greatly benefitted by the enlarged error feedback environment (more improvement on speed and spatial variability within the second exposure phase).

No group main effect or interactions were found when comparing the difference between six catch trials and their baseline, suggesting that both two groups showed similar learning on motor planning and speed. For after-effects, independent *t*-tests revealed significant results in controls on DE, DIST, MT, and RMSE (*p* range from <.001 to 0.043). The motor difficulties group also showed significant findings in DE, MT, and RMSE (*p* range from <.001 to 0.041). These results suggest that both groups displayed positive learning in the enlarged condition. No significant main effect or interactions were found in the comparisons between groups for after-effects (post-exposure with last learning block, post-exposure with baseline), implying that participants with motor difficulties displayed similar adaptability in the enlarged visual feedback condition with controls.

Hypothesis 1-3: Adults with motor difficulties would show stronger adaptability in the enlarged visual feedback condition than they do in the regular condition. The differences between feedback conditions would not be found in the controls.

During the baseline, participants with motor difficulties displayed similar performance with controls. There were no significant differences in DE, DIST, MT, and RMSE. There was a significant main effect for group found in RT (F = 4.54, *p* = 0.043), suggesting that compared to controls, participants in the motor difficulties group spend less time planning their movement at the baseline. There were no other main effects or interactions found for groups (*p* range from 0.340 – 0.768) and conditions (*p* range from 0.093 – 0.891).

In exposure phases, significant main effects of conditions were found for DIST (F = 53.62, *p* <.001), MT (F = 129.26, *p* <.001), and RMSE (F = 10.97, *p* = 0.003). There was no main effect of group or interaction between group and conditions. The results suggest that participants in both groups moved faster and made fewer spatial errors in the regular condition than in the enlarged setting. When examining the catch trials, no main effect for or interactions involving condition were found. For after-effects analyses, there was a significant main effect of condition in RMSE (F = 5.70, *p* = 0.025) and a significant interaction of group*condition in RMSE (F = 4.74, *p* = 0.039). Post hoc analysis revealed significant differences between the enlarged and regular condition in the motor difficulties group (adjust *p* = 0.039) but not in controls (adjust *p* = 1.000), which suggests that participants with motor difficulties displayed stronger after-effects on the spatial control in the enlarged setting, implying that those participants benefit more from the doubled error visual feedback than in the regular setting (Figure 6).

Specific Aim 2: Relationship between Motor Abilities and Adaptability

Hypothesis 2: Instead of group comparison, the ADC was treated as a regressor. The adaptability in the regular condition would be strongly influenced by ADC scores while the adaptability in the enlarged condition would not be affected by ADC scores. Overall, *the degree of motor deficit severity would have a negative relationship with adaptability.*

Regular condition. The relationships between motor abilities and adaptability were examined using a mixed model linear regression, with ADC total score being treated as a continuous variable (i.e., a regressor). Results revealed that there was a significant main effect for block (β range from -25.131 to -0.838, all p <.001) in the exposure phases, suggesting improvement across the fourteen blocks of exposure for all variables among all participants (Figure 7). The performance on 6 catch trials showed significance on DIST, MT, and RMSE (all p<.001). The outcome suggested that in the regular condition, participants spent more time to complete the catch trials and made more spatial errors than in the previous learning trials across the exposure phases (Figure 8).

The relationships between motor ability and adaptation performance were examined among all participants. Analyses showed that there was no main effect for ADC total score in the regular condition exposure phase, except for RT (β = -1.710, p < .001), which suggests that participants with higher ADC scores spent shorter planning time to complete the exposure trials. Interestingly, significant interactions between ADC score and mean of the block for RMSE (p < .001) were found. Participants with higher ADC scores made more spatial errors across exposure blocks than the lower scorers, which suggested that participants with more severe motor deficits showed less adaptability (i.e., worse spatial control) than those with better motor ability.

Comparisons on the mean of the first three post-exposure trials and the mean of the baseline as well as the last learning block revealed significant main effects of ADC on DE (β = -0.452, p = 0.015) and RT (β = -2.820, p = 0.002). Similar results were found in the comparisons between the mean of the first three post-exposure trials and the mean of the baseline (DE: β = -0.318, p = 0.048; RT: β = -2.978, p = 0.003). The findings suggest that participants with higher ADC scores showed less after-effect on motor planning than the lower ADC scorer, implying that the degree of motor deficit has a negative relationship with adaptability in regular condition.

Enlarged condition. In the enlarged condition (double rotation), significant main effects of block (β range from -30.578 to -0.863, all variables p <.001) were found in the learning phase across the fourteen blocks (Figure 7). The RMSE across 6 catch trials (p = 0.056) was approaching significance (Figure 8). To assess the relationship between ADC total score and adaptation performance, regression analysis showed a significant main effect of ADC score in RMSE (β = 0.155, p = 0.014) and RT (β = -1.186, p = 0.017), suggesting participants with higher ADC scores reacted faster and made more spatial errors throughout the exposure trials. The ADC x block interaction on MT revealed that improvement of the movement time across blocks among higher ADC scorers was much more pronounced than lower scorers (p = 0.011). The results implied that participants with better motor ability show stronger adaptability in the enlarged condition as well. There were no significant main effects or interactions revealed by examining catch trials and after-effects during the enlarged condition.

Enlarged vs. regular condition. The statistical analysis showed no significant condition and ADC effects at the baseline phases for all variables (p range from 0.114 to 0.406). In exposure phases, significant main effect of conditions were found for DIST (F = 52.33, p <.001), MT (F = 132.77, p <.001), and RMSE (F = 11.62, p = 0.002). These results suggested that participants moved faster, straighter, and made fewer spatial errors in the regular condition than in the enlarged condition (Figure 7). In other words, participants spent more time to finish trials with error-doubled visual feedback rotation, and the movement distance in total was far longer than in the regular condition. However, analyses revealed significant interaction of block*condition in DIST ($F = 1.80$, $p = 0.043$) and MT ($F = 8.60$, $p < .001$), suggesting that participants showed continuous improvement in the regular condition while they were disrupted dramatically during the second exposure phases when error-feedback was doubled in the enlarged condition (Figure 7). There were no other significant main effects or interactions found by examining catch trials and after-effects.

Chapter 5: Discussion

In the field of motor learning, a large number of studies have focused on children with and without motor difficulties. Researchers have devoted themselves to uncover the mechanism of motor learning, to explore the critical factors which influence the learning processes and the causes of motor deficits, to understand the impacts on children with motor difficulties and the burdens on the parents and our society, and actively develop suitable interventions to facilitate learning and decrease the negative impacts on those children's daily living. It is known that a great amount of "clumsy children" still struggle with their coordination difficulties at their late adolescent or early adulthood, and demonstrate negative impacts on social and occupational activities (Cantell et al., 1994; Cousins & Smyth, 2003; Hellgren et al., 1994). Unfortunately, very few studies can be found on the persistent learning difficulties throughout the adolescent and adulthood. The present study is one of the few studies focused on motor learning deficits in adulthood, and it is the first study examining the influence of error augmentation on participants with motor difficulties using the kinematic adaptation paradigm. The idea of introducing enlarged visual feedbacks to subjects was inspired by a series kinematic adaptations studies in children with DCD and healthy young adults (e.g., Kagerer et al., 2006; Wei et al., 2005), and several force adaptation studies in stroke patients (e.g., Patton et al., 2006).

Previous works using computer-manipulated adaptation paradigm have claimed that "noisy" visuomotor mapping underlies the learning deficits of children with DCD in adaptation tasks (Kagerer et al. 2004; Kagerer et al. 1997). Kagerer et al. (2004) reported that children with DCD were less affected by the feedback distortion and showed less learning than the controls. In one of their follow-up studies, Kagerer et al. (2006) found that the children with DCD did not appear to be able to utilize the small error signals provided during the gradual perturbation, but they could perform as well as the typically developing children when exposed to larger error signals in the abrupt visuomotor perturbation. These results suggest that children with DCD are able to adapt to visuomotor distortion as long as the error messages are significantly distinguishable.

One potential method to compensate the “noisy” visuomotor controls is to provide enlarged visual feedbacks during learning (Gomi & Kawato, 1993; Patton & Huang, 2012; Wei et al., 2005). Patton and colleagues suggested that introducing larger errors by robotic devices could facilitate adaptive training in patients with hemiparetic stroke (Patton, Kovic, & Mussa-Ivaldi, 2006; Patton, Stoykov, et al., 2006). Wei et al., (2005) further demonstrated that the idea of error augmentation could be used in kinematic adaptation on healthy controls. This approach was succefully improved the rate and extent of motor learning of visuomotor rotations on healthy subjects (Wei et al., 2005). The authors stated that intensifying error could lead to larger signal-to-noise ratios for sensory feedback and self-evaluation (Wei et al., 2005).

Clear evidence on the benefit of large feedbacks in previous force adaptation studies (Patton et al., 2006; Wei et al., 2005) lead me to ask whether adults with motor difficulties can benefit from enlarged visual feedbacks during learning. Thus, the current study focused on young adults with and without motor difficulties, aimed to examine the relationship between motor abilities and adaptability in computer adaptation tasks in enlarged and regular visual feedback conditions. The overall goal for the current project was to test whether adults with motor difficulties could better adapt to changes in the computer adaptation tasks when visual feedback was enlarged. Related issues were discussed in the following section in the order of the proposed specific hypotheses.

Specific Aim 1: Group Difference between Participants with Motor Difficulties and Controls

Hypothesis 1-1: Adults with motor difficulties would show less adaptability than controls in the regular feedback condition.

In the regular feedback condition (30 degree during exposure phases), all the participants, regardless of their motor ability, were able to show improvement in the adaptation task. However, participants with motor difficulties did not improve their spatial variability as fast as the participants with normal motor ability (i.e. significant group x block interaction on RMSE, Figure 3 & 5). They also showed less adaptability than controls on motor planning (significant results of after-effect on RT, Figure 6). Such findings were consistent with previous work on children with DCD. For example, Kagerer and colleagues found significant group differences between children with DCD and controls during the exposure phase for initial directional error (IDE) and movement length (ML), representing poorer planning and spatial accuracy in children with DCD, respectively (Kagerer et al. 2004; Kagerer et al. 1997). They also found that children with DCD demonstrated poorer performance at the baseline and less improvement during the exposure relative to their baseline performance, which indicated that children with DCD were less affected by the visual feedback distortion than the controls. Combining their results, the authors concluded that children with DCD might lack a sufficiently well-defined reference, thus the performance errors during the exposure could not be corrected and updated to the visuomotor maps.

Since most of the children with motor difficulties cannot “grow out” of their deficits, adults with motor difficulties have a great possibility to learn motor tasks with the “noisy” internal maps in their adulthood. In the visuomotor adaptation tasks presenting in the current study, young adults might start with a much broader, or noisier, visuomotor map that absorbed the distorting effects of the visuomotor incompatibility. As the results, the performance errors encountered during exposure phase could be detected and/or corrected, therefore preventing a sufficiently well-defined update of the visuomotor maps.

Furthermore, the young adults with motor difficulties in current study demonstrated significant faster reaction time (RT) and movement time (MT) during the exposure phase, and significant faster RT at the post-exposure phase compared to controls. Such short planning period during the entire task might be due to the fact that they were aware of their issues on planning, thus developing a strategy of reacting and moving faster to compensate their deficits. They tended to rely more on the feedback mechanism rather than the known defective feed-forward mechanism. Significant after-effect on RT provided a strong support for the positive learning and successful compensation of the feedback processes for the “noisy” visuomotor mapping.

Hypothesis 1-2: Adults with motor difficulties would show similar adaptability in the enlarged visual feedback condition to controls.

In the enlarged feedback condition, participants with motor difficulties showed overall improvement across the entire exposure phases, although they displayed less improvement on movement speed and spatial variability in the enlarged feedback exposure (significant group x block interaction on MT and RMSE, Figure 4 & 5). Consistent with the current hypothesis, no group differences were found on catch trials and after-effect, suggesting no learning differences between two motor ability groups.

Similar with the regular feedback condition, participants with motor difficulties demonstrated similar patterns of spending less time in planning (shorter RT), making more spatial errors (larger RMSE), and drawing relatively “messy” lines (longer DIST) during the doubled-feedback exposure phase than healthy adults. The finding further supports the conclusion that participants with motor difficulties tend to rely more on visual feedbacks than their initial planning ability during learning. Thus, it is not surprising that they have better chance to detect the error messages and correct their movement when the visual feedbacks are significantly distinguished.

In accordance with Wei et al. (2005), the present study provides evidence that participants with and without motor difficulties both displayed positive learning in the enlarged condition. As Wei et al. (2005) claimed in their work, double visual feedback could improve the amount of motor control on visuomotor adaptation task (the change of the trajectory errors; significant effect on RMSE across trials and after-effect in this study), the finding of the current study further suggest that error augmentation also facilitate motor learning for both groups (significant results on catch trials and after-effect for DE, MT, and RMSE). No significant main effect or interactions on any variables in the comparisons between groups for after-effects implied that participants with motor difficulties displayed similar adaptability (both planning and control aspects) in the enlarged visual feedback condition with controls. The performance at the end of the task suggest that adults with motor difficulties can successfully adapt to the visual rotation just as normal controls in response to enlarged visual feedbacks.

Hypothesis 1-3: Adults with motor difficulties would show stronger adaptability in the enlarged visual feedback condition than they do in the regular condition. The differences between feedback conditions would not be found in the controls.

Comparing performance between two feedback conditions, both groups showed faster movement time, shorter movement trajectory, and less spatial errors during the exposure phase in the regular condition. Significant group x condition interaction on

RMSE for after-effect suggested that participants with motor difficulties had a stronger adaptation in the enlarged conditions while the controls had similar adaptation in two feedback conditions (Figure 6). The finding suggests that participants with motor difficulties benefit from the enlarged feedback in helping them better control their movement, but not in planning aspect. Thus, the hypothesis 1-3 was partially supported in terms of spatial control.

Consistent with previous findings on healthy controls and stroke patients, the present study confirmed the applicability of error augmentation in the kinematic adaptation tasks and its favorable outcomes on healthy subjects. This study further provides promising evidence that error augmentation can facilitate motor learning using kinematic adaptation paradigm, especially for adults with motor difficulties. Although participants from both groups all benefit from the error augmentation, participants with motor difficulties displayed significant improvement on spatial controls, suggesting that introducing larger visual feedbacks can be an effective intervention for facilitating motor learning in terms of spatial control.

Feedback has been served to develop accurate error detection and correction mechanisms, thus humans can evaluate intrinsic feedback (provided by sensory system) and compare it with extrinsic feedback (provided by external sources). For patients with motor difficulties, their “noisy” sensorimotor system may impede the detection of extrinsic feedback and weaken their intrinsic feedback, hence lose the chance to correct the error. Therefore, introducing augmented feedback can be a method to increase the probability of detection of extrinsic feedback and larger the signal-to-noise ratios for intrinsic feedback.

An additional explanation for how enlarged feedback is beneficial for the control of movement and acquisition of motor skills is that feedback has long been believed to function as a reward. Enlarged feedback may have a strong energizing role to make a task seem more interesting and enjoyable. Besides the motivation effects, feedback may work as a guidance to help participants complete a task. Doubled visual feedback presenting in the study may provide more information to the participants in terms of guidance and motivation, thus lead to better adaptation performance.

Specific Aim 2: Relationship between Motor Abilities and Adaptability

Hypothesis 2: Instead of group comparison, the ADC was treated as a regressor. The adaptability in the regular condition would be strongly influenced by ADC scores while the adaptability in the enlarged condition would not be affected by ADC scores. Overall, the degree of motor deficit severity would have a negative relationship with adaptability.

One may argue that the cutoff point of ADC score for group comparison was arbitrary due to the heterogeneity of motor difficulties. Thus, to further examine the relationship between motor abilities and adaptability, I treated the motor ability measure (i.e., ADC) as a regressor instead of group comparsions. It was hypothesized that the adaptability in the regular condition would be strongly influenced by ADC scores while the adaptability in the enlarged condition would not be affected by ADC scores. The significant main effect of ADC for after-effect on DE and RT was found in the regular condition but not in the enlarged condition supported this particular hypothesis. However, an ADC x block interaction on RMSE in the regular condition and an ADC x block on MT in the enlarged condition suggested that motor ability affected not only the regular feedback condition, but also the enlarged feedback condition. The hypothesis 2 was partially not supported when the adaptability was measured by the improvement during the exposure phases.

The severity of motor deficit seemed to be related to the adaptability on the adaptation tasks. Participants with severer motor impairment spent less time in planning, made more spatial errors throughout the learning phase, and displayed smaller after-effects at the post-exposure phase, suggesting insufficient sensorimotor map updating and unstable learning pattern. The finding using regression model confirmed the main conclusions based on group comparison that participants with severer motor deficits tend to rely on their motor control ability based on the visual feedback rather than planning ability. These results support the idea that the severity of motor deficit has negative impacts on adaptation, which influences the effectiveness and accuracy of motor learning.

General Discussion

There are several possibilities that may explain the influence of motor deficits on visuomotor adaptation in presenting study. One explanation is the visual signals used for learning may be noisier in participants with motor difficulties, therefore, the process of error correction and adaptation is compromised. Inherently unreliable neuromuscular noise can influence one’s motor adaptation, motor coordination, and motor learning (Wann & Turnbull, 1993). A study on children with DCD suggested that children with motor difficulties do not appear to recognize their movement errors either during baseline or learning trials, therefore do not correct their errors (Kagerer et al., 2004). Although the visual signals in the neuromuscular system may still remain noisy and impede learning efficiency and adaptability (Cousins & Smyth, 2003; Kagerer et al., 2006; Kirby & Sugden, 2010), adults with motor difficulties seem to acquire coping strategies of fully utilizing the feedback information to compensate their ”noisy” neuromuscular mappings. Therefore, recognizing the intact feedback processing among adults with motor difficulties and developing appropriate strategies base on their strengths (for example, introducing enlarged visual feedback) will likely be the most beneficial avenue for intervention.

Another possibility is that the adaptive mechanisms in adults with motor difficulties may have less plasticity, which affected the capacity of their system to encode the changes in a permanent way. This reduced capacity to establish or modify the visuomotor maps is supported by studies which indicating a relationship between compromised cerebellar functionality and coordination problems (Gramsbergen, 2003; Ivry, 2003). The deficiency in cerebellar processing may be the result of reduced plasticity in this network, hence gives rise to an unstable learning curve. Given the heterogeneity in motor performance found in adults with motor difficulties, the possibility that other structures might also be involved should not be ruled out.

In addition, it has been suggested that cognitive functions, e.g., working memory, play a crucial role in motor learning in adults (Bo & Seidler, 2009), aging (Bo, Borza, & Seidler, 2009), and children with DCD (Alloway, 2007; Alloway, Rajendran, & Archibald, 2009). Alloway et al., (2007, 2009) found that motor impairments in children with DCD were associated with selective deficits in visuospatial short-tern and working memory, and the deficits were significantly worse than their verbal short-term memory (Alloway, 2007; Alloway et al., 2009). Therefore, further studies are needed to examine the importance of cognitive functions, working memory, and general motor functions among adults with motor difficulties.

Overall, the presenting study showed that adults with motor difficulties had relatively unstable adaptative pattern and less efficient learning in the regular visual feedback condition compare to controls; however, they were able to perform a similar level of adaptation compared to normal controls in the enlarged condition by successful compensation of the feedback processes for the “noisy” visuomotor mapping. The severity of motor deficit has negative impacts on adaptation, which influences the effectiveness and accuracy of motor learning. Participants with lower motor ability showed less adaptability than those with higher motor ability, particularly in the regular feedback condition, suggesting that introducing larger feedback can increase the adaptability for adults with lower motor ability. In sum, it may be beneficial to provide enlarged visual feedback to promote motor learning for adults with motor difficulties. Further research is needed to improve our understanding of the effectiveness of this approach and the underlying mechanism of error augmentation in kinematic adaptation.

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Figure 1 ADC Score Distribution Among 27 Participants.

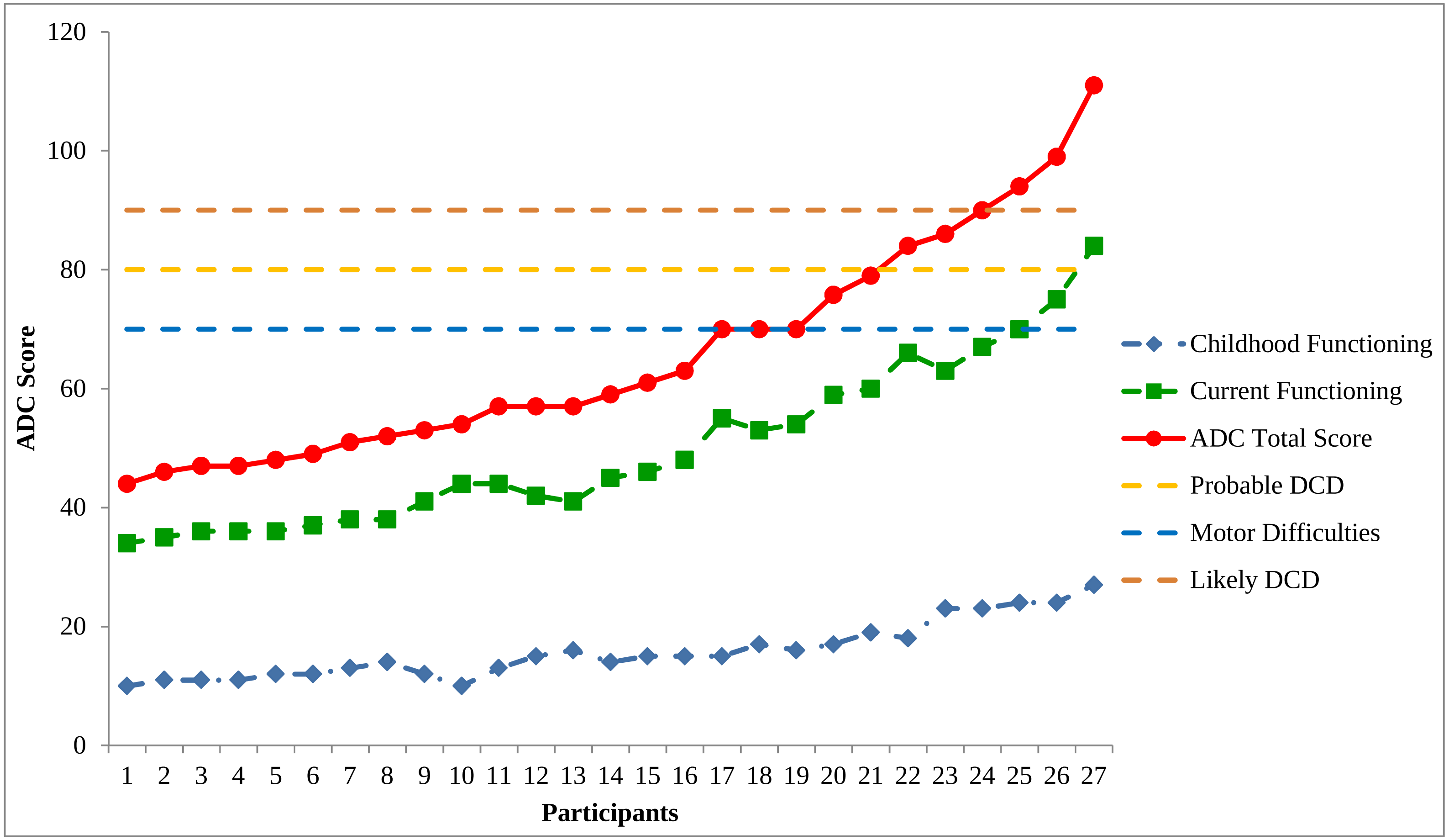


Figure 2 Illustration of the Visuomotor Adaptation Task.

It is a “center-out” drawing task. Participants were asked to move a cursor as fast and as straight as possible from home positions (shown as yellow dot in this simplify figure) to target positions (green dot) displayed on the computer screen. The target position was one of eight green dots (diameter of the picture: 1 cm) appearing randomly in one of eight locations (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) around the home position (distance from home position to target: 10 cm). The home position was visible throughout the duration of the testing session. The target appeared as soon as the cursor stays in the home position motionless for 1 second, and disappeared as soon as the cursor enters the target picture.

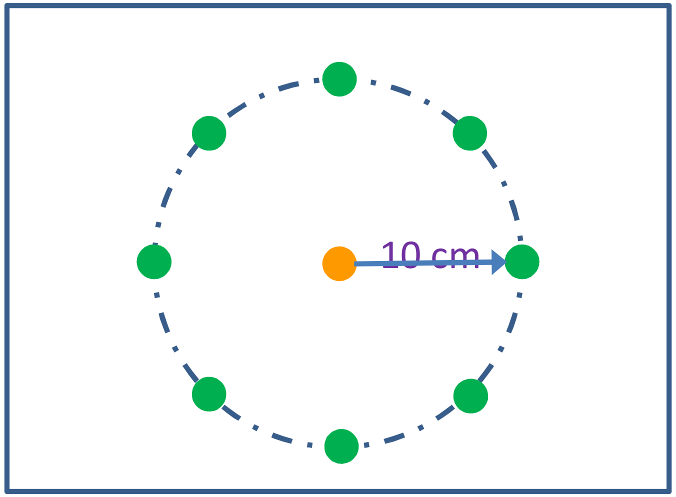
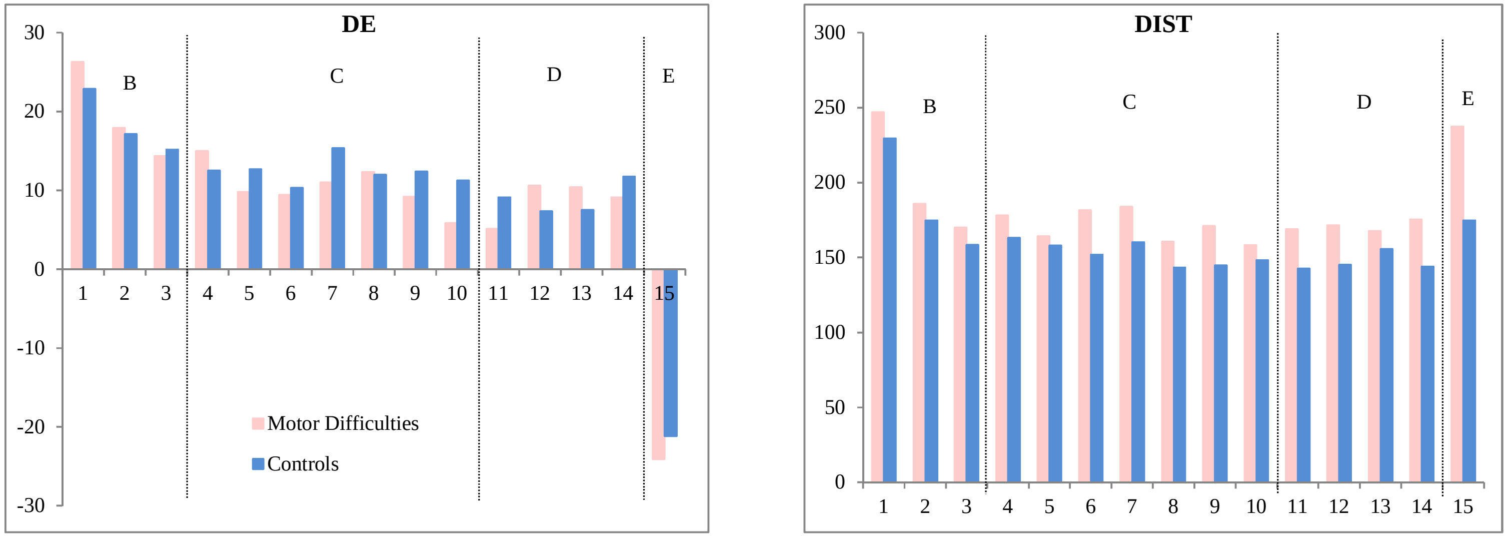
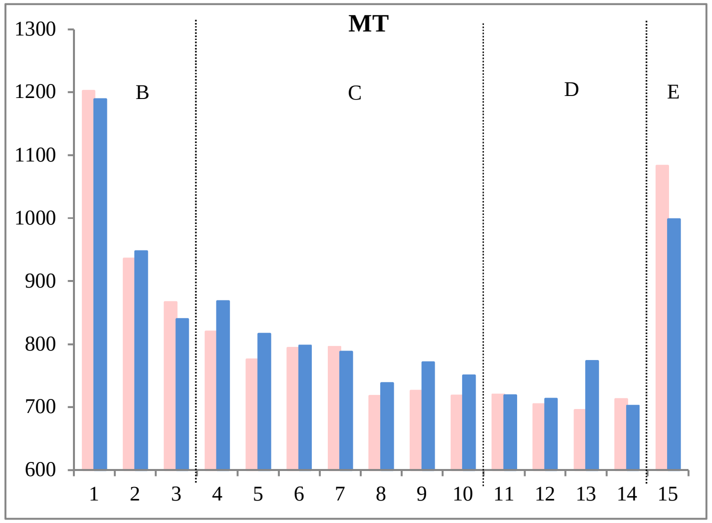


Figure 3 Block Mean Differences between Exposure, Post-exposure Phases and Baseline in the Regular Condition for Participants with and without Motor Difficulties.

Mean differences between each block and its baseline for all variables: (B) first exposure phase (block 1-4: 30° visual feedback rotation); (C) second exposure phase (block 5-10: 30° visual feedback rotation); (D) third exposure phase (block 11-14: 30° visual feedback rotation); (E) post-exposure phase (block 15: after-effect). Positive DE values indicate a clockwise deviation of the joystick from the optimal (straight) line between home-position and target, and negative values indicate a counterclockwise deviation, suggesting after-effects.

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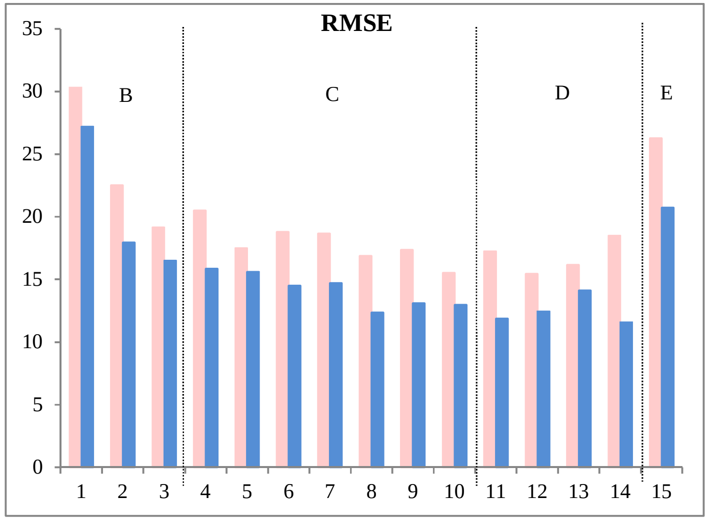
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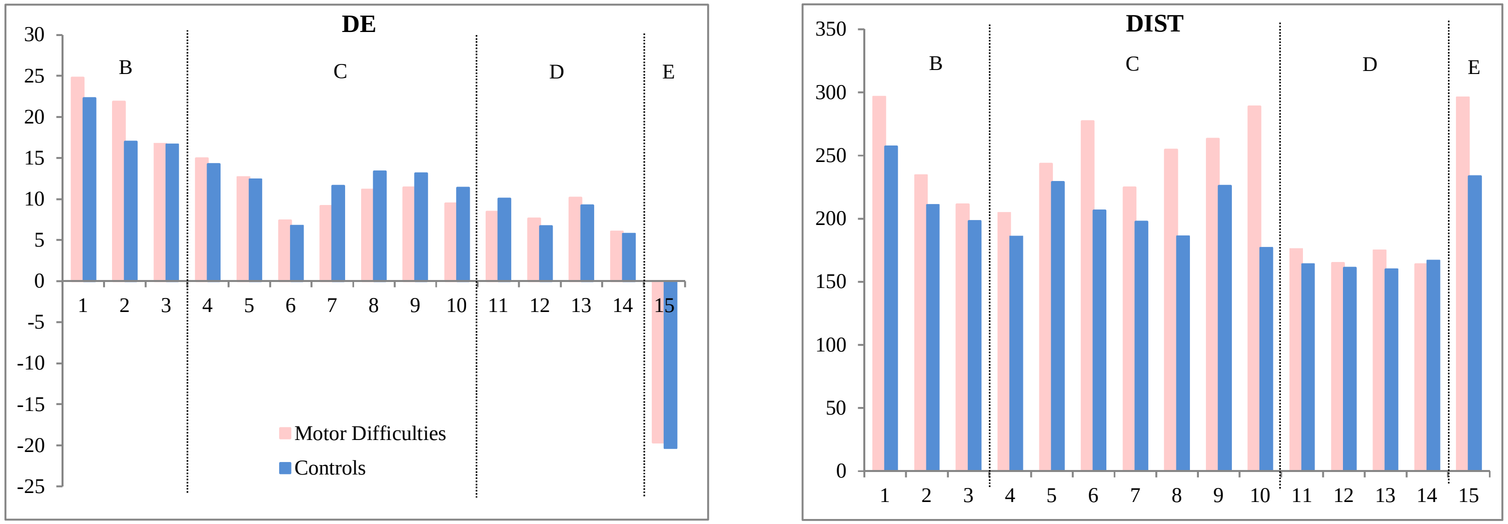
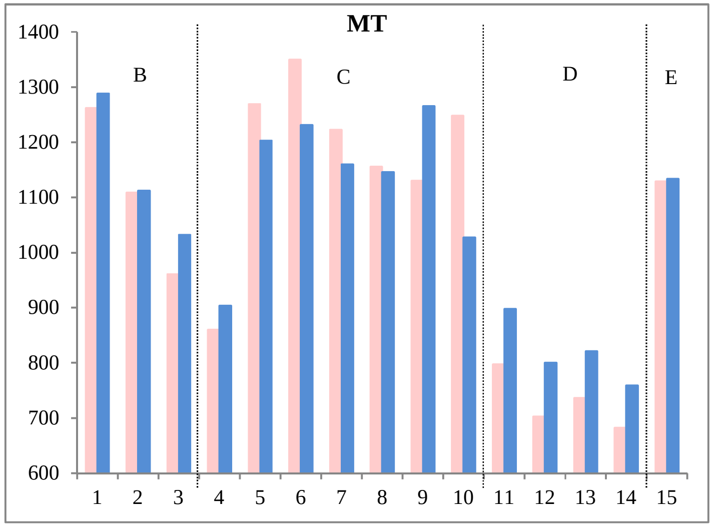
Figure 4 Block Mean Differences between Exposure, Post-exposure Phases and Baseline in the Enlarged Condition for participants with and without motor difficulties.

Mean differences between each block and its baseline for all variables: (B) first exposure phase (block 1-4: 30° visual feedback rotation); (C) second exposure phase (block 5-10: error-doubled visual feedback rotation); (D) third exposure phase (block 11-14: 30° visual feedback rotation); (E) post-exposure phase (block 15: after-effect). Positive DE values indicate a clockwise deviation of the joystick from the optimal (straight) line between home-position and target, and negative values indicate a counterclockwise deviation, suggesting after-effects.

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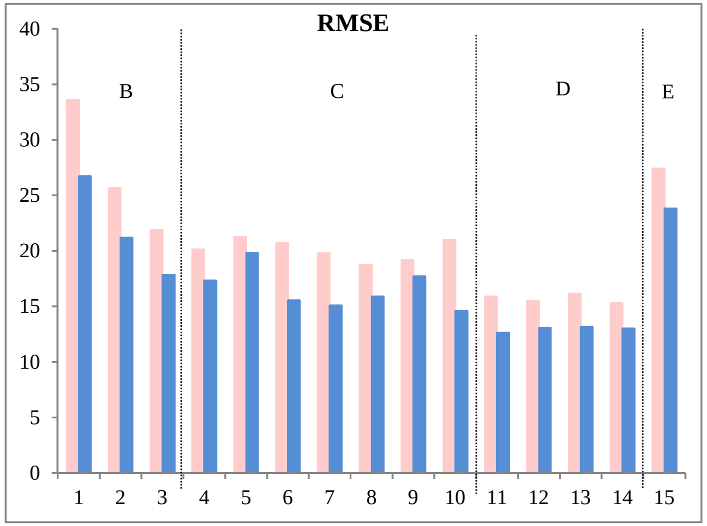
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Figure 5 Interactions between Blocks and Groups for MT and RMSE in the Exposure Phases in the Regular and Enlarged Conditions.

Estimated least squares means of each block for MT and RMSE: (B) first exposure phase (block 1-4: 30° visual feedback rotation); (C) second exposure phase (block 5-10: 30° vs. error-doubled visual feedback rotation); (D) third exposure phase (block 11-14: 30° visual feedback rotation).

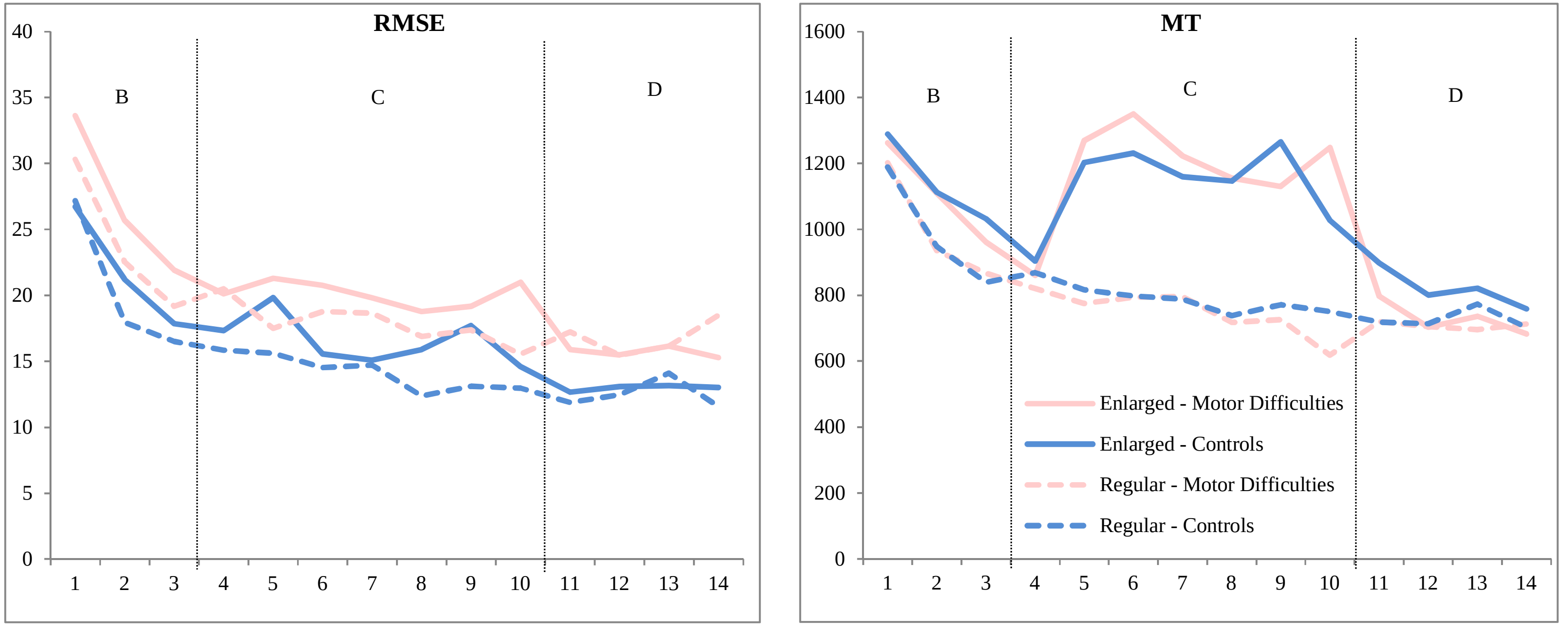


Figure 6 Group Comparisons of the After-effects in the Enlarged and Regular Conditions.

Estimated least squares means of the difference between post-exposure phase and baseline.

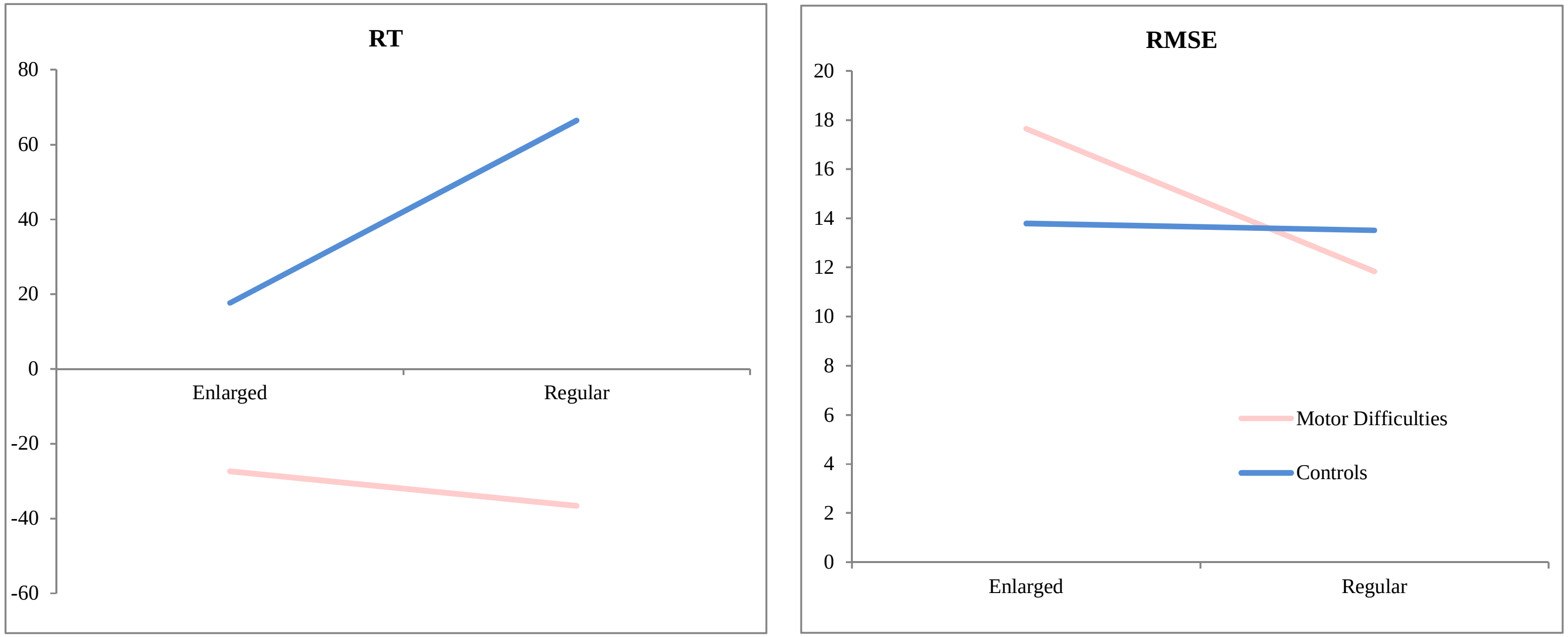
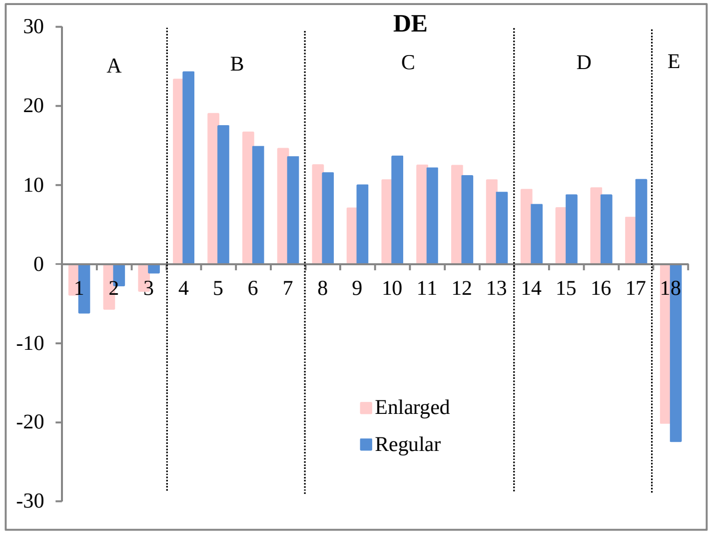
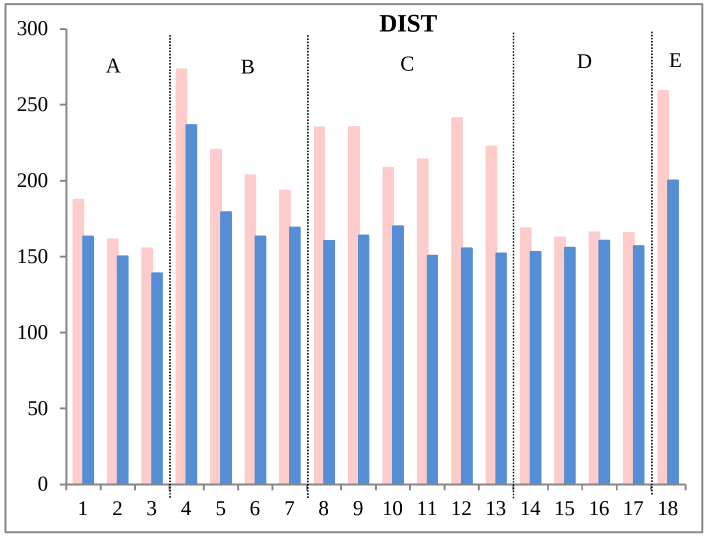
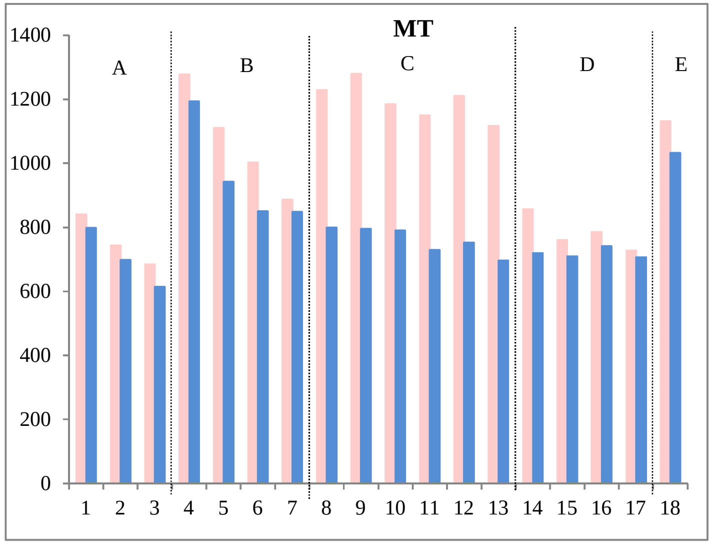


Figure 7 Comparisons of Block Means between Enlarged and Regular Conditions among All Participants.
Means of each variable for each block: (A) pre-exposure phase (baseline, block 1-3); (B) first exposure phase (block 4-7: 30° visual feedback rotation); (C) second exposure phase (block 8-13: 30° vs. error-doubled visual feedback rotation); (D) third exposure phase (block 14-17: 30° visual feedback rotation); (E) post-exposure phase (after-effects, block 18). Positive DE values indicate a clockwise deviation of the joystick from the optimal (straight) line between home-position and target, and negative values indicate a counterclockwise deviation, suggesting after-effects.






MT
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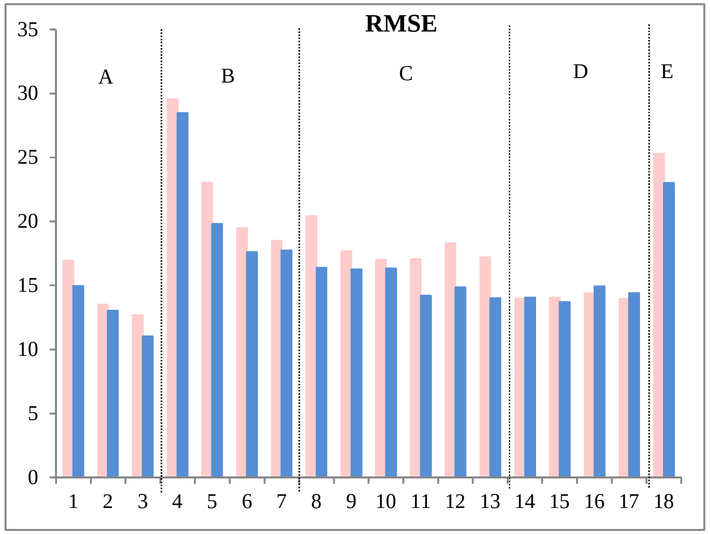
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18


RMSE
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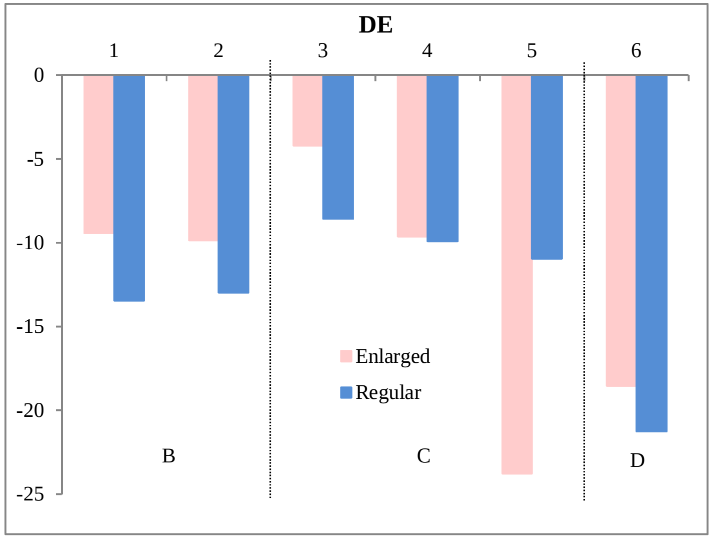
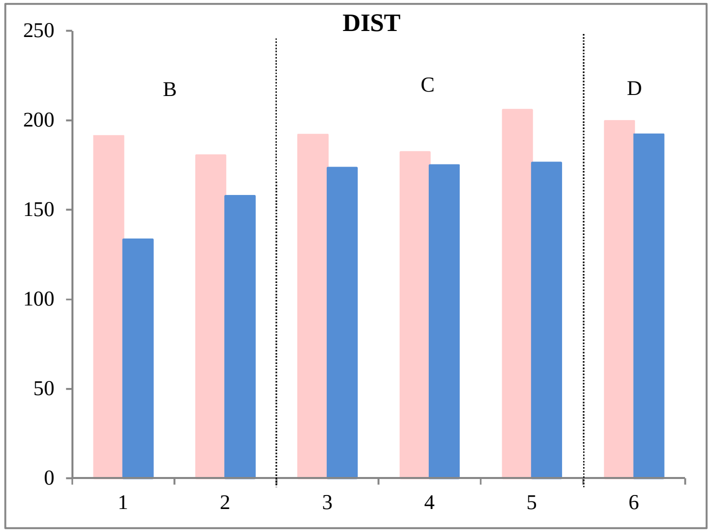
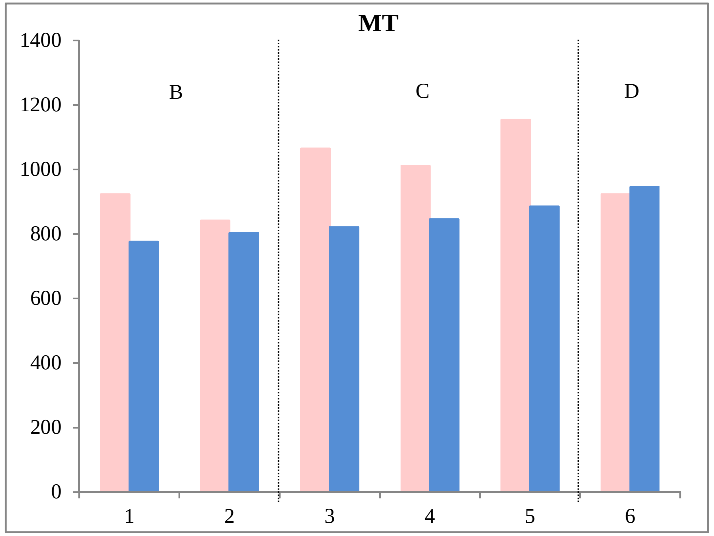
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

Figure 8 Comparisons of Catch Trials between Enlarged and Regular Conditions among All Participants.
Means of each variable for each catch trial: (B) first exposure phase (2 trials: 30° visual feedback rotation); (C) second exposure phase (3 trials: 30° vs. error-doubled visual feedback rotation); (D) third exposure phase (1 trial: 30° visual feedback rotation). Negative DE values indicate a clockwise deviation of the joystick from the optimal (straight) line between home-position and target, suggesting after-effects.



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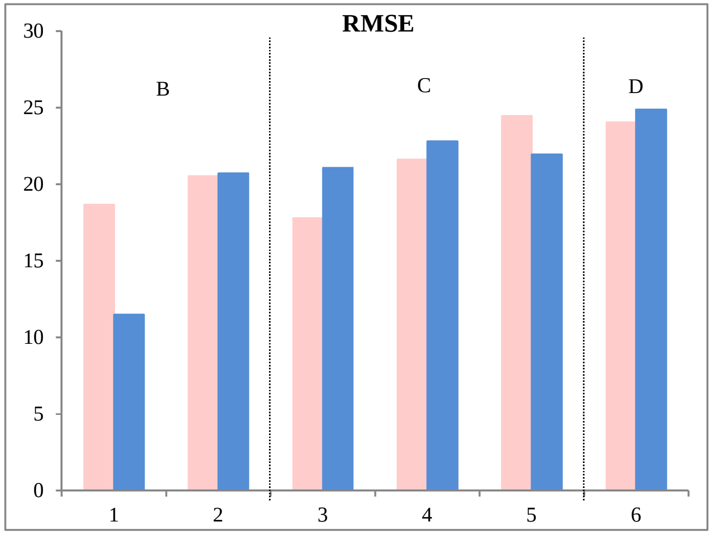
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