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Faculteit Revalidatiewetenschappen

master in de revalidatiewetenschappen en de kinesitherapie

Masterthesis

Aging and bimanual motor learning, including the effect of task difficulty on this relationship

Sara Kessels
Arne Lekens

Scriptie ingediend tot het behalen van de graad van master in de revalidatiewetenschappen en de kinesitherapie, afstudeerrichting revalidatiewetenschappen en kinesitherapie bij neurologische aandoeningen

PROMOTOR :
Prof. dr. Koen CUYPERS

BEGELEIDER :
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2024
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Acknowledgements

We would like to thank dra. Maud Beeckmans and Prof. dr. Koen Cuypers for their guidance during the realization of this dissertation. We also want to express our gratitude towards UHasselt for providing us with numerous educational opportunities over the past five years. In addition, we would like to thank our family and friends for their support and encouragement while writing this dissertation. Finally, we especially want to thank each other for the commitment, support and teamwork during this adventure together.

Context

This dissertation is written in the context of "In-depth scientific internship and master's thesis", which is a course offered by UHasselt. The field of research is motor control, cognition and brain. This dissertation is situated within an ongoing doctoral study of Maud Beeckmans and Sara Ferreira. The research was conducted at the Gasthuisberg campus of UZ Leuven and at De Nayer in Leuven. This dissertation was conducted by two students, Sara Kessels and Arne Lekens. In consultation with their supervisor dra. Maud Beeckmans and their promoter Prof. dr. Koen Cuypers, they determined three research questions. Every part of this dissertation was carried out by both students.

Abstract

As reaching an older age is a current phenomenon in our society, it is important to have a deeper understanding of the changes that occur during aging. The aims of this dissertation are to look deeper into the influence of aging on bimanual motor performance, to explore the relationship between aging and bimanual motor learning and to investigate the influence of task difficulty on these age-related changes in bimanual motor learning. This study involved a total of 46 participants, consisting of 22 younger and 24 older adults. All participants received two weeks of training on a bimanual task. Before, during and after this training period, the motor performance on this bimanual task was assessed through progression tests. Based on the data analysis, it was concluded that aging causes a decrease in bimanual motor performance. Furthermore, aging has different effects on bimanual motor learning in different stages of learning, with a negative effect of aging found in the early stages of learning and no significant effect of aging in later stages of learning. The bimanual motor learning gap between younger and older adults becomes larger as task difficulty increases, with older adults being disadvantaged.

Keywords: aging, bimanual motor learning, bimanual motor performance, task difficulty, bimanual tracking task

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1. Introduction

Bimanual skills require the coordination of both hands together to manipulate objects, where each hand has its own function (Taylor et al., 2024). Because many of these bimanual skills develop spontaneously during childhood, we consider them easy and take them for granted. However, these skills hide a considerable behavioral complexity and depend on sophisticated neural architecture (Maes et al., 2017). Aging seems to cause impaired bimanual coordination and reduce both movement quantity and quality (Shizuka et al., 2025; Seidler et al., 2010). Furthermore, the capacity to learn simple procedural motor tasks appears to remain intact to some extent in normal aging (Bhakuni & Mutha, 2015). Learning bimanual skills can be useful because they play an important role in daily life (Gerloff & Andres, 2002). Therefore, this will be a key topic in this dissertation. The ability to move both our hands in a structured and organized manner in space and time determines our functional independence. This is why bimanual coordination is important for everyone, but especially for older people (Maes et al., 2017). Furthermore, it is widely known that reaching an older age is a current phenomenon in our society (Garaschuk, 2021).

> The number and proportion of people aged 60 years and older in the population is increasing. In 2019, the number of people aged 60 years and older was 1 billion. This number will increase to 1.4 billion by 2030 and 2.1 billion by 2050. This increase is occurring at an unprecedented pace and will accelerate in the coming decades. (World Health Organization: WHO, 2020)

Therefore, it is important to have a deeper understanding of the changes that occur during aging (Garaschuk, 2021).

In the introduction of this dissertation, the influence of aging on bimanual motor performance will be discussed. Additionally, the relationship between aging and general motor learning will be examined. Then, this dissertation will zoom in more specifically on bimanual tasks. The relationship between aging and bimanual motor learning and the influence of task difficulty on this relationship will be investigated. Finally, at the end of this introduction, the aims and research approach of this dissertation will be discussed.

1.1 Bimanual motor performance and aging

When looking at bimanual motor performance, Monteiro et al. (2017) and Van Hoornweder et al. (2022) stated that older adults (OA) showed poorer bimanual motor performance on a bimanual coordination task in comparison to younger adults (YA). More specifically, a large variety of bimanual continuous coordination tasks has shown consistent age-related declines in performance accuracy and/or speed (Bangert et al., 2010; Boyke et al., 2008; Leinen et al., 2016; Moes et al., 1995; Pauwels et al., 2015; Serbruyns et al., 2013; Solesio-Jofre et al., 2014; Spirduso & Choi, 1993; Stelmach et al., 1988; Voelcker-Rehage & Willimczik, 2006). Furthermore, a longer reaction time and a longer movement time were reported in OA in comparison to their younger peers in non-repetitive discrete bimanual tasks (Maes et al., 2017). Another study also found that the response times were significantly longer in OA compared to YA, this time in serial bimanual tasks (Bhakuni & Mutha, 2015). All these findings support the idea of decreased bimanual motor performance in OA in comparison to YA.

In contrast to the findings above, the bimanual performance levels between YA and OA were comparable in a continuous bimanual circle drawing task performed in the study of Summers et al. (2010). This outcome, in which OA performed as well as YA, was expected in this study. Since conclusions on the effect of aging on bimanual motor performance were inconsistent, further research will be conducted within this dissertation.

1.2 Motor learning and aging

Motor learning can be defined as any experience-dependent improvement in performance. Multiple brain regions contribute to motor learning: prefrontal cortex, supplementary motor area, presupplementary motor area, primary motor and somatosensory cortex, dorsal and ventral premotor cortex, posterior parietal cortex, hippocampus, cerebellum and basal ganglia. These regions assist in the process of goal-setting, selection or execution (Krakauer et al., 2019).

Many studies show that OA need more time to reach a certain level of motor performance in comparison to YA due to their lower rate of learning, i.e. decreased motor learning rate (Ren et al., 2012). In another study, the learning rate was lower in OA in comparison to YA when looking at a learning period of four days (Rueda-Delgado et al., 2019). And also according to Voelcker-Rehage (2008), YA were significantly faster with motor learning in comparison to OA. Interestingly, OA often have an equal potential to acquire motor skills as YA, they just need more time to do so (Ren et al., 2012). So in conclusion, OA have a decreased motor learning rate compared to YA when it comes to general motor learning.

A possible explanation for this decreased motor learning rate is that high-level areas of the brain that are responsible for motor learning become more vulnerable as one ages. Furthermore, when looking deeper into this decreased rate of motor learning, aging seems to have less negative effects on motor learning in the case of implicit motor learning, in which there is no awareness of the learning (Ren et al., 2012).

1.3 Bimanual motor learning and aging

A distinction between three categories of bimanual tasks can be made (Schmidt & Lee, 2005): 1) Discrete bimanual tasks include movements with a clear beginning and end, and with a clear pause inserted between each movement (Bangert et al., 2010; Kennerley et al., 2002; Schmidt & Lee, 2005). Examples of a discrete task are opening a bottle or peeling a banana. 2) Serial bimanual tasks are made up of various actions being executed in series, for example a tennis serve. The importance of the order of these actions is the most defining characteristic of this category (Maes et al., 2017). 3) Continuous bimanual tasks involve simultaneous movements which are repeated over time without a pause in between (Bangert et al., 2010; Kennerley et al., 2002). Juggling is a clear example of this last category (Maes et al., 2017). This dissertation will focus on a bimanual tracking task (BTT), a continuous bimanual task that will be further explained later in this dissertation.

Unlike the relationship between motor learning and aging, controversy has been found regarding the relationship between bimanual motor learning and aging. Several studies show that OA are slower at acquiring bimanual coordination skills compared to YA (Perrot & Bertsch, 2007; Ren et al., 2012). On the other hand, there are studies with serial bimanual tasks showing that OA have a similar learning rate to YA (Bhakuni & Mutha, 2015; Hoff et al., 2015). Also when looking at a continuous bimanual task, YA and OA demonstrated similar gains in motor performance across six training sessions, indicating an equal learning rate (Voelcker-Rehage & Willimczik, 2006). Contradictory this, Monteiro et al. (2017) concluded that the improvement in bimanual motor performance on a BTT after two weeks of training was larger for OA in comparison to YA. This higher bimanual motor learning rate in OA is likely due to lower performance levels before training in this age group (Monteiro et al., 2017). Taking stages of learning into account, Adab et al. (2018) stated that OA learned at a higher rate than YA during the early stages of bimanual motor learning, while YA learned faster during the later stages of bimanual motor learning. These controversial findings are the reason for this dissertation to further investigate the relationship between aging and bimanual motor learning rate.

The influence of task difficulty might be crucial to fully understand this relationship between bimanual motor learning and aging. Age-related effects on bimanual motor learning seem to interact with task-related factors. Within discrete bimanual tasks, Maes et al. (2017) reported that age-related effects on motor learning gradually emerge when a task gets more complex. Voelcker-Rehage (2008) mentioned that the learning rates for low-complexity tasks are very similar across age groups. More complex tasks often reveal differences in learning rates between YA and OA, with OA having lower learning rates than YA. This supports the idea of an increasing difference in bimanual motor learning between YA and OA as the task gets more difficult, with OA being disadvantaged. Contradictory this, Zvornik et al. (2024) stated that task complexity did not interact with bimanual motor learning for both YA and OA when performing a bimanual visuomotor task. The controversy present is an indication for further research, which will be carried out by this dissertation.

1.4 Aims and research approach

The aim of the first research question of this dissertation is to look deeper into the influence of aging on bimanual motor performance. The aim of the second research question is to explore the relationship between aging and bimanual motor learning. Also, as the aim of the third research question, the influence of task difficulty on these age-related changes in bimanual motor learning will be investigated.

Based on the findings above from previous studies, the following three hypotheses were formed. The first hypothesis concerning the influence of aging on bimanual motor performance, states that aging has a negative impact on bimanual motor performance (Monteiro et al., 2017; Bangert et al., 2010; Boyke et al., 2008; Leinen et al., 2016; Moes et al., 1995; Pauwels et al., 2015; Serbruyns et al., 2013; Solesio-Jofre et al., 2014; Spirduso & Choi, 1993; Stelmach et al., 1988; Voelcker-Rehage & Willimczik, 2006; Maes et al., 2017; Bhakuni & Mutha, 2015). The second hypothesis regarding the relationship between aging and bimanual motor learning states that both YA and OA will improve their bimanual motor performance through training, but YA will have a higher bimanual motor learning rate than OA (Perrot & Bertsch, 2007; Ren et al., 2012). The third hypothesis relating to the influence of task difficulty on the relationship between aging and bimanual motor learning states that age-related effects on bimanual motor learning, which cause OA to learn at a significantly slower rate than YA, will be larger in more difficult tasks (Maes et al., 2017; Voelcker-Rehage, 2008).

To answer our research questions, a group of OA and YA will be subjected to the same bimanual motor training program for two weeks using a BTT. Six task conditions, namely line11, line31, line13, zigzag, wave and flamingo, will be applied in this training program. These BTT conditions will be divided into three levels of task difficulty. The bimanual motor performance will be assessed during three progression tests (PT). These will take place before, during and after the bimanual motor training.

This dissertation begins by describing the methods used to find an answer to the research questions. It will then go on to review the results found, which will thereafter be discussed. Finally, a conclusion will be formed based on the findings of this study.

2. Methods

2.1 Participants

After excluding two participants diagnosed with mild cognitive impairment, the study involved a total of 46 participants. These participants were divided into two groups: 22 YA and 24 OA.

The recruitment of potential participants took place through a radio announcement and flyers that were spread online and in public places. Only large groups of people were addressed instead of individuals to avoid social desirability bias. Thereafter, the selection of suitable participants was carried out using several questionnaires, inclusion and exclusion criteria.

An assessment of cognitive function was performed using the Montreal Cognitive Assessment (MoCA). Depression was assessed via the following questionnaires: Beck Depression Inventory - Second Edition (BDI-II), Geriatric Depression Scale - 15 items (GDS-15). The BDI-II was administered only to the YA, and the GDS-15 only to the OA. Furthermore, the Edinburgh Handedness Inventory (EHI) was used to assess hand preference.

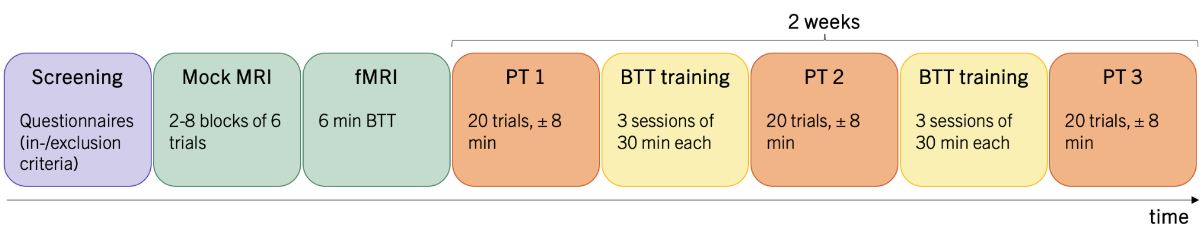
Furthermore, the applied inclusion criteria are: right-handed (EHI ≥ 50), aged 25 to 40 for the YA, aged 65 to 80 for the OA, normal or corrected-to-normal eyesight, Dutch as a native language or Dutch proficiency for more than 10 years. Additionally, some exclusion criteria were applied: contra-indications for MRI; smoked in the past 10 years; pregnant; medication with an impact on the brain; regular bimanual coordination activities such as gaming or playing the piano in the past five years for more than five hours per week; experience in the used BTT; current or past alcohol or drug addiction; cognitive impairment (MoCa ≤ 25); depression (GDS-15 > 4 or BDI-II > 13).

2.2 Procedure

The general procedure of this study is composed of several successive steps. First of all, the participant gets introduced to the BTT in an MRI mock scanner. They had to perform a minimum of two blocks of the same six trials. Starting from the second block, once an accuracy score of 15% on that block was achieved, the familiarization in the MRI mock scanner was stopped. Up to six additional blocks were allowed to be performed if needed to reach the 15% accuracy score. This minimum percentage was set arbitrarily to ensure that participants understood the task. After performing eight blocks of six trials in total, familiarization in the MRI mock scanner was stopped anyway. This approach causes equality in terms of participants' understanding of the task, but also a disparity in terms of BTT experience. A detailed description of a BTT trial, the BTT conditions and the associated difficulty levels will follow later in this dissertation. Another time familiarization with the BTT occurred was during an fMRI scan, which was conducted as part of the broader study these people participated in. Thereafter, a BTT training will be performed at home. Before, during and after this motor training, participants will be required to complete a PT, as shown in Figure 1. Based on the BTT accuracy score of these PT, the change in their bimanual motor performance due to the BTT training will be measured. Bimanual motor performance, represented by the BTT accuracy score, will be the main outcome measure of this study. A more detailed description of the equipment used, the applied training protocol, and the PT will follow.

Figure 1

Timeline of the General Procedure of the Study



Note. MRI: Magnetic Resonance Imaging; fMRI: functional Magnetic Resonance Imaging; BTT: bimanual tracking task; PT: progression test; min: minutes.

The methodology of this study is based on the research conducted by Monteiro et al. (2017) and Adab et al. (2020). The study of Monteiro et al. (2017) used a similar BTT setup with a support surface on which there were two dials with a diameter of five centimeters. By rotating the handle of these dials with both hands simultaneously, a cursor can be moved on the computer screen. Clockwise (CW) rotations of the left-hand dial moved the cursor upward, while counterclockwise (CCW) rotations moved it downward. The participants were instructed to follow a moving target dot as accurately as possible along a predetermined trajectory. Each trial began with a two-second presentation of the target pathway and target dot, before the dot started moving at a constant speed for 10 seconds. Real-time visual feedback on the participants' performance was given in the form of a red line. The past cursor position was displayed by this red line up to one second after the cursor was at that particular spot. At the end of each trial, the screen remained black for about three seconds before the next trial began, thus standardizing the waiting time. In the BTT training, which consisted of multiple BTT trials, four possible conditions were used. Each condition had a specific shape of the predetermined trajectory representing a different task difficulty. The BTT training sessions were spaced over two weeks.

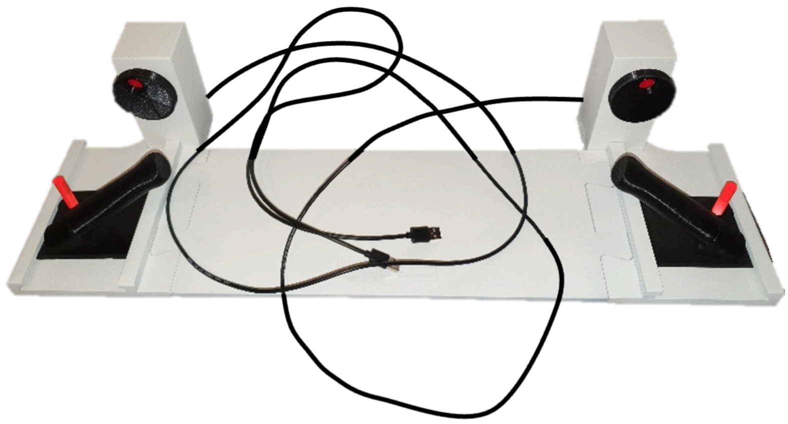
Adab et al. (2020) used a BTT, in which participants had to move a cursor on a computer screen by rotating two dials with their hands. The rotation direction and speed could differ between the dials. Each BTT trial lasted for not more than 15 seconds and consisted of three phases: a two-second planning phase, a ten-second execution phase, and a three-second intertrial phase. Performance was finally expressed in terms of a performance score. A greater performance score was achieved when following the target trajectory closely while controlling the speed accurately. Lower performance scores reflected deviations from the target dot. The calculation of the BTT score used in this dissertation is similar to the calculation of the performance score from the study by Adab et al. (2020) and will be discussed further later in this dissertation, under the subtitle BTT score.

2.2.1 Equipment

The BTT setup consists of a supported surface featuring two handles that participants can hold in their hands (Figure 2). These handles are positioned at an adjustable distance from two dials with a diameter of five centimeters. The dials contain a small circular groove in which the participants can place their index fingers. This way, participants can rotate the dials using both their index fingers, allowing them to control the movement of a cursor on the computer screen. The right dial controls right-left movement of a cursor over the x-axis on a laptop screen, namely CW for movements to the right and CCW for movements to the left. On the other hand, the left dial controls up-down movement over the y-axis, namely CW for upward movements and CCW for downward movements of the cursor. This way, by moving with two index fingers simultaneously, participants can create diagonal lines and other shapes. The information from the rotating dials is transferred to a laptop via a USB cable. In this study, a laptop with LabVIEW 8.5 (National Instruments, Austin, Texas, USA) was used.

Figure 2

BTT Setup



Note. *A supported surface with two handles and two dials that can be connected to a laptop via a USB cable. ©Melina Hehl*

2.2.2 BTT trial

At the start of each BTT trial, a target line and a white target dot at the beginning of this line are presented on the laptop screen for two seconds (Figure 3). Because the white target dot is not moving yet, the participants can prepare themselves during this planning phase of the trial. Hereafter, the white target dot will start moving at a constant speed over the pathway. This constant speed can vary per trial and thus determine the duration of the trial execution. The goal is to stay as close as possible to this moving target dot with the cursor that is controlled by the rotation of the dials. A red line represents the trajectory covered by the participant. After this execution phase of the BTT trial, a feedback period of two seconds will take place, in which the participants can reflect on their performance. Between different trials, the screen will be completely black for three seconds.

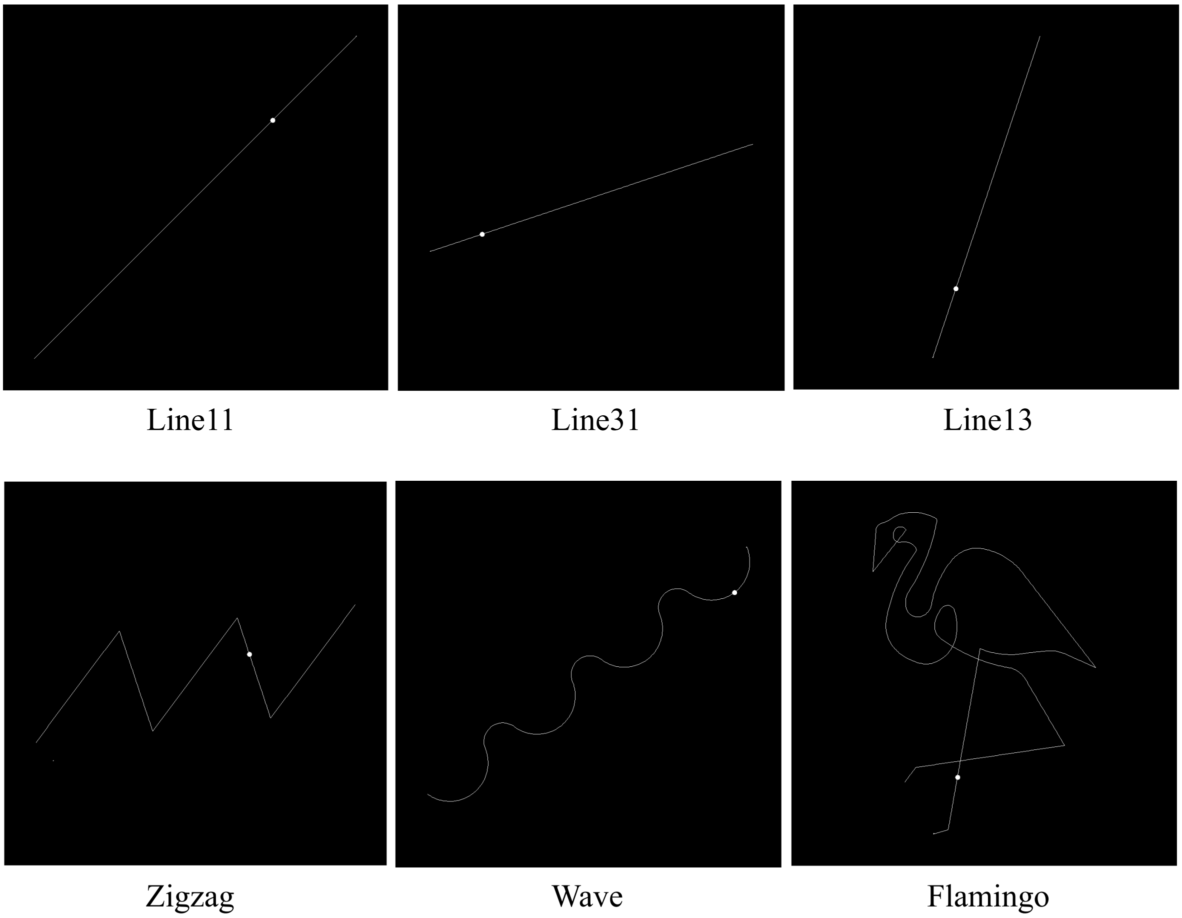
2.2.3 BTT conditions and difficulty levels

In this study, a distinction can be made between six conditions of the BTT, in which task difficulty increases (Figure 3). Different levels of motor control and planning are required to perform these conditions: 1) Line11, in which both index fingers rotate at the same speed and in the same direction; 2) Line31, in which the left index finger rotates three times as fast as the right index finger and both index fingers rotate in the same direction; 3) Line13, in which the right index finger rotates three times as fast as the left index finger and both index fingers rotate in the same direction; 4) Zigzag, in which the rotation direction of the left dial changes quickly multiple times in order to follow the angles of the target pathway; 5) Wave, in which the rotation direction and speed of both dials change gradually so the waves can be followed by the cursor; 6) Flamingo, in which straight lines, angles and curved lines are included. These BTT conditions could be performed in two directions: either as shown in Figure 3, or as a horizontal mirroring of the trials of Figure 3.

The six BTT conditions can be divided into three difficulty levels. Difficulty level one, which is the easiest level, includes condition line11, in which the rotation speed of both dials is the same. Difficulty level two includes conditions line31 and line13, because the rotation speed of one dial is three times greater than the rotational speed of the other dial in these two conditions. Difficulty level three contains conditions zigzag, wave and flamingo. In these, a change in rotation direction is present in at least one hand, which causes them to be the most difficult conditions.

Figure 3

BTT Trials of the Six BTT Conditions



Note. One trial of each BTT condition. ©Maud Beeckmans

2.2.4 Training protocol

After the familiarisation discussed previously, the BTT training was performed at home over a period of about two weeks. Minor deviations were present regarding this time span. The training consisted of six training sessions of 30 minutes. The participants were asked to distribute the training sessions as evenly as possible throughout the entire training period of two weeks, in which the sessions had to be spread over a minimum period of seven days. It was not allowed to perform two training sessions on the same day. In total, the six training sessions counted 34 training blocks of about five minutes each. The trial order during these training blocks was random. When a PT was administered on the same day as a training session, the training session consisted of five training blocks. This was the case for the first and fourth training sessions. When no PT was conducted on the same day, the training session consisted of six training blocks. This applied to the second, third, fifth and sixth training sessions.

The BTT training was individualized by implementing training levels, in which higher training levels were related to an increased task difficulty. This increased difficulty was achieved by adding more difficult conditions to the BTT training and/or varying speeds between trials of one training block. This way, the training level of the participant determined which conditions were trained. The flamingo condition was not yet practiced during the BTT training; it only appeared in the PT. Overall, the training level increased as the participant achieved higher accuracy scores and therefore performed better on the BTT. Each participant started training at level one during the first five-minute training block. During all the following training blocks, they progressed two levels if they obtained a BTT score of 65 percent or higher, regressed one level if their BTT score was lower than 40 percent and stayed in the same training level if they had a BTT score of 40 to 65 percent. After each training block, participants were given feedback saying “Congrats, you are going to the next level!” if they proceeded to the next level and “Keep trying!” if they did not.

A short break was automatically included after each training block or PT. Participants could choose when to resume the training. However, they were asked to limit the duration of their breaks between the training blocks. Furthermore, participants could pause the training session at any moment by pressing a random key on the keyboard, but were instructed to only do this in case of an emergency.

2.2.5 Progression tests

In total, three PT were conducted: one before, one during and one after the BTT training. The first PT took place on the same day as the first training session before any training occurred. At this point, the participants were already exposed to the BTT in the MRI mock scanner and during an fMRI. The fMRI was conducted during the broader study, but this data was not a part of this dissertation. The second PT was administered on the same days as the fourth training session, when three out of six training sessions were finalised. The third PT was conducted on a separate day after the last training session. Each PT took about eight minutes and consisted of the same 20 trials in the same order: six times line11, four times line31, four times line13, two times zigzag, two times wave and two times flamingo. The goal of these PT was to assess bimanual motor performance. By comparing these three measuring points later on, bimanual motor learning could be assessed.

2.3 Data analysis

The data collected in the PT described above will be used to draw conclusions related to the three research questions of this dissertation. The calculation of the BTT score will be explained below. Then, the processing of the collected data, i.e. the BTT scores of the PT, will be discussed. Finally, hypothesis testing, including the statistics applied, will be described.

2.3.1. BTT score calculation

The BTT score lies between zero and 100 and will be higher when the participant manages to keep the cursor close to the moving white target dot throughout the entire trial. To calculate the BTT score, which represents bimanual motor performance in this dissertation, the performance score as used in Adab et al. (2020) will be multiplied by a correction factor. The performance score from Adab et al. (2020) can be calculated by dividing the number of points of the target line that were covered by the total number of points involved in forming the target line and then multiplying this by 100. So, for example, if 20 out of 31 points were covered, the performance score would be (20/31) x 100 = 64.5% (Adab et al., 2020). The correction factor mentioned above is the difference between one and one-fifth of the mean distance to the target line. Thanks to this correction, participants receive a lower score when their cursor moves parallel to the target line instead of on the target line. Thus, by using this corrected formula, the BTT score obtained will be lower if the cursor moves faster or slower than the target dot or if the cursor deviates from the target line.

2.3.2 Data processing

For each participant, the scores from each BTT trial for all three PT were included in the data analysis. Before statistics could be performed, the collected data was put into the correct format in Microsoft Excel for Mac version 16.96.1. To perform the statistics concerning research question one, the data of PT one was put into a Microsoft Excel file. Additionally, the data from all three PT was put into a second Microsoft Excel file to find answers to research questions two and three. The statistical software used in this dissertation is SAS JMP Pro 17.

2.3.3 Hypothesis testing

The mean BTT scores of PT one of YA and OA were continuous data and both age groups were independent and each contained more than 20 but less than 30 participants. Therefore, several statistical approaches were possible to find an answer to research question one, concerning the influence of aging on bimanual motor performance, depending on the normality and variances of both age groups. In case of normal distribution in both age groups and equal variances, a two-sample t-test would be performed. Furthermore, the Welch test would be most suitable in the case of normal distribution in both age groups and unequal variances. A third possible statistical approach is the Wilcoxon rank-sum test, which would be performed when there is no normal distribution in at least one age group (Meesen & Verstraelen, 2022).

Concerning research questions two and three, the differences in BTT scores between two PT were continuous data. Task difficulty and age group, which are both categorical variables, and their interaction could possibly have an influence on this difference in BTT score between two PT. Furthermore, the difference in BTT score between two PT was measured for three difficulty levels per participant; therefore the measurements were dependent. This explains why a linear mixed model seemed suitable (Meesen & Verstraelen, 2022). Task difficulty, age group and their interaction were included in the initial linear mixed model: bimanual motor learning ability = β0 + b0i + β1*age group + β2*task difficulty + β4*age group*task difficulty + Ɛij. Bimanual motor learning ability is the difference in BTT score, which represents motor performance, between two PT.

3. Results

3.1 Study population

The total study sample consisted of 46 participants, distributed between two age groups: 22 YA and 24 OA. The age of the YA ranged from 25 to 40 years, while the age of the OA ranged from 65 to 79 years. In terms of gender distribution, there was a slightly higher representation of males (n = 13; 54.167%) compared to females (n = 11; 45.833%) in the group of OA. Among YA, the ratio of men to women was equal. Furthermore, the years of education among all participants spanned from nine to 27 years. Within the group of YA, the years of education ranged from 10 to 27 years, while they ranged from nine to 22 years in OA. There was no length, weight and BMI data available from one YA and one OA. The demographic characteristics of the study sample are presented in Table 1.

Table 1

Demographic Characteristics of the Participants

Characteristic	YA (n=22)	OA (n=24)
Age (yrs)	31.50 [Q1: 25.75 - Q3: 38.00]	69.00 [Q1: 67.00 - Q3: 72.75]
Gender	Female: 11 Male: 11	Male: 13 Female: 11
Education (yrs)	17.00 [Q1: 15.75 - Q3: 18.25]	15.50 [Q1: 12.00 - Q3: 17.75]
Length (m)	1.713 ± 0.065	1.708 ± 0.068
Weight (kg)	70.176 ± 11.762	72.609 ± 12.527
BMI	23.048 ± 4.006	23.913 ± 4.316

Note. Mean and standard deviation were reported for normally distributed variables length, weight and BMI (mean ± SD). Median and interquartile range were reported for not normally distributed variables age and years of education (median [Q1 - Q3]). YA: younger adults; OA: older adults; yrs: years; BMI: body mass index; m: meter; kg: kilograms; n: number of participants.

3.2 Influence of aging on bimanual motor performance

Before conducting the statistics, the normal distribution of both age groups had to be tested first. Depending on the normality, it might also be necessary to test whether the variances of both groups were equal. The mean BTT scores of PT one were normally distributed in YA, as the p-value of the Shapiro-Wilk test was .889. However, in OA, the mean BTT scores of PT one were not normally distributed, as the p-value of the Shapiro-Wilk test was .028. Because there was no normal distribution in one age group, the Wilcoxon rank-sum test was most suitable to find an answer to research question one.

The level of bimanual motor performance will be represented by the BTT score of the first PT (Table 2). At this point, no BTT training had taken place yet, but the participants were already exposed to the BTT in the MRI mock scanner and during the fMRI. The Wilcoxon rank-sum test that was conducted revealed a significant difference in BTT score of the first PT between YA and OA ($p < .001$). The magnitude of this significant difference in motor performance will be represented by the mean difference in BTT score of the first PT between the two age groups, which is 13.684 with a standard error of 2.692.

Table 2

BTT Scores of the First Progression Test for Younger and Older Adults

Age Group	M	SD	SE	95% CI
YA	26.056	11.155	2.378	[21.110 - 31.002]
OA	12.372	6.046	1.261	[9.758 - 14.987]

Note. YA: younger adults; OA: older adults; M: mean BTT score of the first progression test; SD: standard deviation; SE: standard error; %: percentage; CI: confidence interval.

3.3 Relationship between aging and bimanual motor learning

In order to analyze the influence of aging on bimanual motor learning, the following linear mixed model was conducted: bimanual motor learning ability = $\beta0 + b0i + \beta1$*age group + $\beta2$*task difficulty + $\beta4$*age group*task difficulty + εij. This linear mixed model was run three times, one for each comparison between two PT: PT 2-1, PT 3-2 and PT 3-1. Because there is a higher chance of type one errors when a model is run multiple times, the Bonferroni correction was performed by dividing the significance level of .05 by 3, i.e. the number of times the model was run, which equals .017. Besides, normal quantile plots were used to check for normal distribution for each run of the linear mixed model, i.e. for each comparison between two PT (Attachments 1, 2 and 3). In addition, conditional residual by predicted plots were used to check for homoscedasticity for each run of the linear mixed model, i.e. for each comparison between two PT (Attachments 4, 5 and 6).

The analysis has identified a significant effect of age group on the bimanual motor learning ability for PT 2-1 ($p < .001$) and for PT 3-1 ($p = .001$). When looking deeper into this bimanual motor learning ability between PT one and two, YA improved on average by 11.016 points more than OA. Furthermore, when looking at the bimanual motor learning ability between PT one and three, YA improved on average by 11.360 points more than OA. However, there was no significant effect of age group on the bimanual motor learning ability for PT 3-2 ($p = .869$).

However, the interaction between age group and task difficulty was significant in all three PT comparisons ($p < .001$); therefore this interaction needs to be taken into account when looking at the effect of age group on bimanual motor learning. This significant interaction between age group and task difficulty, which represents the significant influence of task difficulty on the relationship between aging and bimanual motor learning, will be discussed more thoroughly in chapter 3.4 of this dissertation. The influence of aging on bimanual motor learning ability, including the interaction mentioned above, is visualized in Figures 4 and 5.

The average differences in BTT score between two PT, which represent the bimanual motor learning ability, are shown in Table 3 for both age groups. Figure 4 further visualizes this bimanual motor learning ability for YA and OA, for all three comparisons of PT. In addition, Figure 5 visualizes the mean BTT scores per PT, which gives a better view of the bimanual motor performance at which the participants started before motor learning. Therefore, this informative plot about the raw BTT data has added value to interpret the effect of aging on bimanual motor learning.

Table 3

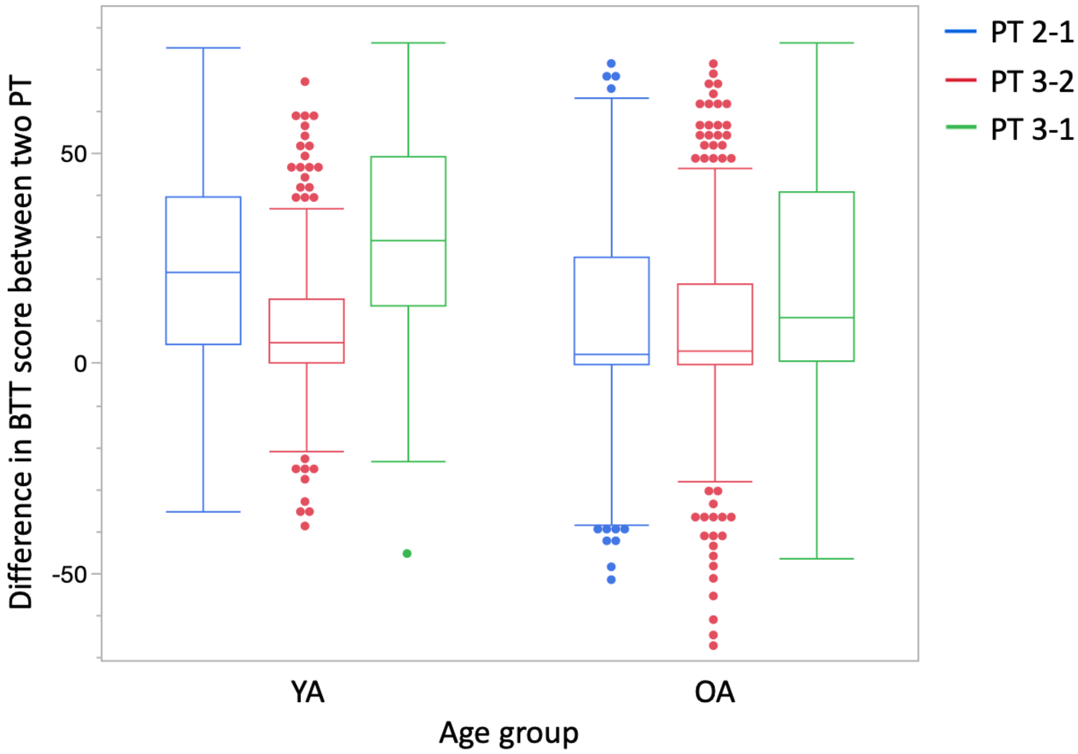
Bimanual Motor Learning in Younger and Older Adults

Age Group	PT comparison	M	SE	95% CI
YA	2-1	23.160	1.351	[20.436 - 25.884]
	3-2	8.217	1.310	[5.577 - 10.857]
	3-1	30.976	1.951	[27.037 - 34.916]
OA	2-1	12.144	1.302	[9.517 - 14.770]
	3-2	7.920	1.223	[5.454 - 10.386]
	3-1	19.616	1.844	[15.889 - 23.344]

Note. The mean improvement in BTT score between two progression tests, which represents bimanual motor learning ability, was reported for each age group. The two progression tests that were compared are visible in the PT comparison column. YA: younger adults; OA: older adults; PT: progression test; M: mean increase in BTT score between two progression tests; SE: standard error; %: percentage; CI: confidence interval.

Figure 4

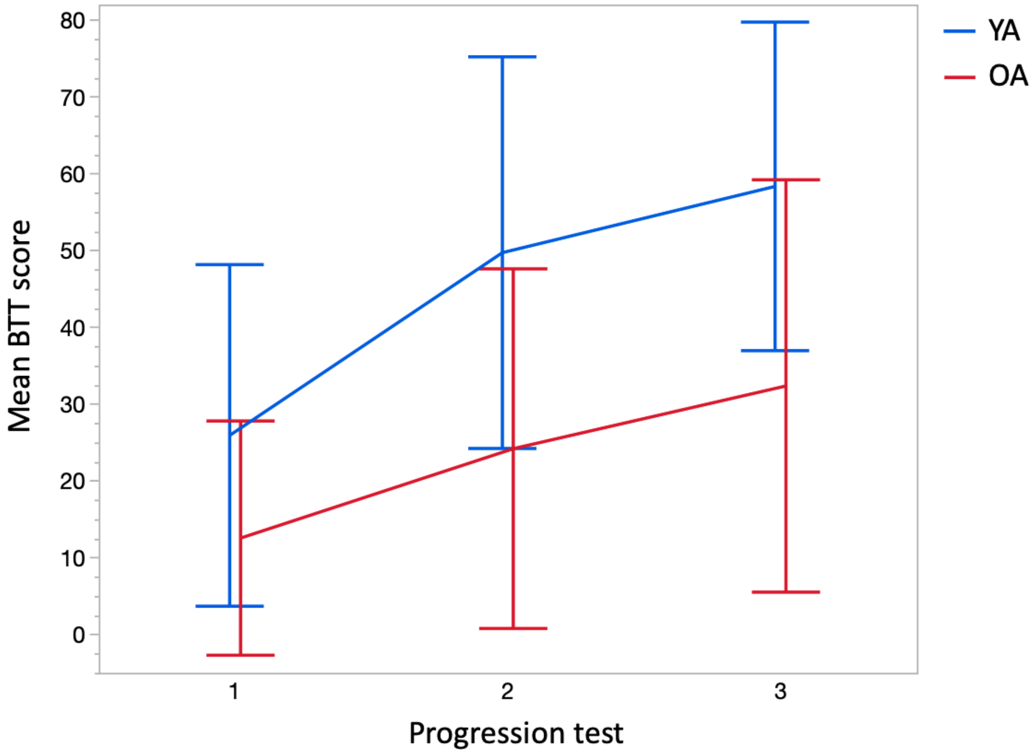
Bimanual Motor Learning Ability per Progression Test Comparison for Younger and Older Adults



Note. The box plots visualize the bimanual motor learning ability, represented by the difference in BTT score between two progression tests, per progression test comparison for younger and older adults. The raw data was added in the form of dots. BTT: bimanual tracking task; PT: progression test; YA: younger adults; OA: older adults.

Figure 5

Bimanual Motor Learning Ability for Younger and Older Adults



Note. The mean BTT scores per progression test were visualized for younger and older adults. The slope of the line between the mean BTT scores of two progression tests represents the bimanual motor learning ability between those two progression tests for a certain age group. The whiskers represent the standard deviation. BTT: bimanual tracking task; YA: younger adults; OA: older adults.

3.4 Influence of task difficulty on age-related changes in bimanual motor learning

Using the same linear mixed model that was mentioned above in chapter 3.3 of this dissertation, the influence of task difficulty on the relationship between aging and the bimanual motor learning ability was analyzed. The p-value of the interaction between age group and task difficulty was < .001 for PT 2-1, PT 3-2 and PT 3-1. Therefore, a significant effect of task difficulty on age-related changes in bimanual motor learning ability was found in all three PT comparisons.

Furthermore, post-hoc tests using the Tukey HSD were conducted to provide an overview of the mean bimanual motor learning ability per difficulty level for both YA and OA for each PT comparison (Tables 4, 5 and 6). These post-hoc tests also look at the significance of the mean differences in bimanual motor learning ability between YA and OA per difficulty level for each PT comparison (Tables 4, 5 and 6). Furthermore, Figures 6, 7 and 8 illustrate the average differences in BTT score between two PT, representing the bimanual motor learning ability, per difficulty level for YA and OA for each PT comparison. In addition, Figure 9 visualizes the influence of task difficulty on the relationship between aging and bimanual motor learning by showing the mean BTT scores per PT for each difficulty level and for both age groups. This gives a better view of the bimanual motor performance at which the participants started before motor learning. Therefore, this informative plot about the raw BTT data has added value to interpret the effect of task difficulty on the relationship between aging and bimanual motor learning.

Table 4

Results PT 2-1

DL	Age Group	M	SE	95% CI	MD	SE	P-value*
1	YA	31.575	1.959	[27.710 - 35.440]	4.688	2.736	.523
	OA	26.887	1.910	[23.118 - 30.656]			
2	YA	26.366	1.794	[22.815 - 29.917]	18.576	2.483	< .001
	OA	7.790	1.716	[4.393 - 11.187]			
3	YA	11.539	2.011	[7.572 - 15.505]	9.785	2.774	.006
	OA	1.754	1.910	[-2.015 - 5.523]			

Note. The mean improvement in BTT score between progression tests one and two, which represents bimanual motor learning ability between those two progression tests, was reported per difficulty level for each age group. PT: progression test; DL: difficulty level; YA: younger adults; OA: older adults; M: mean increase in BTT score between progression test one and two; SE: standard error; %: percentage; CI: confidence interval; MD: mean difference in bimanual motor learning ability between younger and older adults for a certain difficulty level.

* p < .017

Table 5

Results PT 3-2

DL	Age Group	M	SE	95% CI	MD	SE	P-value*
1	YA	3.044	1.815	[-0.541 - 6.629]	-7.144	2.499	.050
	OA	10.188	1.718	[6.797 - 13.580]			
2	YA	8.096	1.665	[4.797 - 11.396]	-2.246	2.280	.923
	OA	10.342	1.558	[7.256 - 13.428]			
3	YA	13.511	1.879	[9.803 - 17.219]	10.280	2.545	.001
	OA	3.231	1.718	[-0.161 - 6.622]			

Note. The mean improvement in BTT score between progression tests two and three, which represents bimanual motor learning ability between those two progression tests, was reported per difficulty level for each age group. PT: progression test; DL: difficulty level; YA: younger adults; OA: older adults; M: mean increase in BTT score between progression test two and three; SE: standard error; %: percentage; CI: confidence interval; MD: mean difference in bimanual motor learning ability between younger and older adults for a certain difficulty level.

* $p < .017$

Table 6

Results PT 3-1

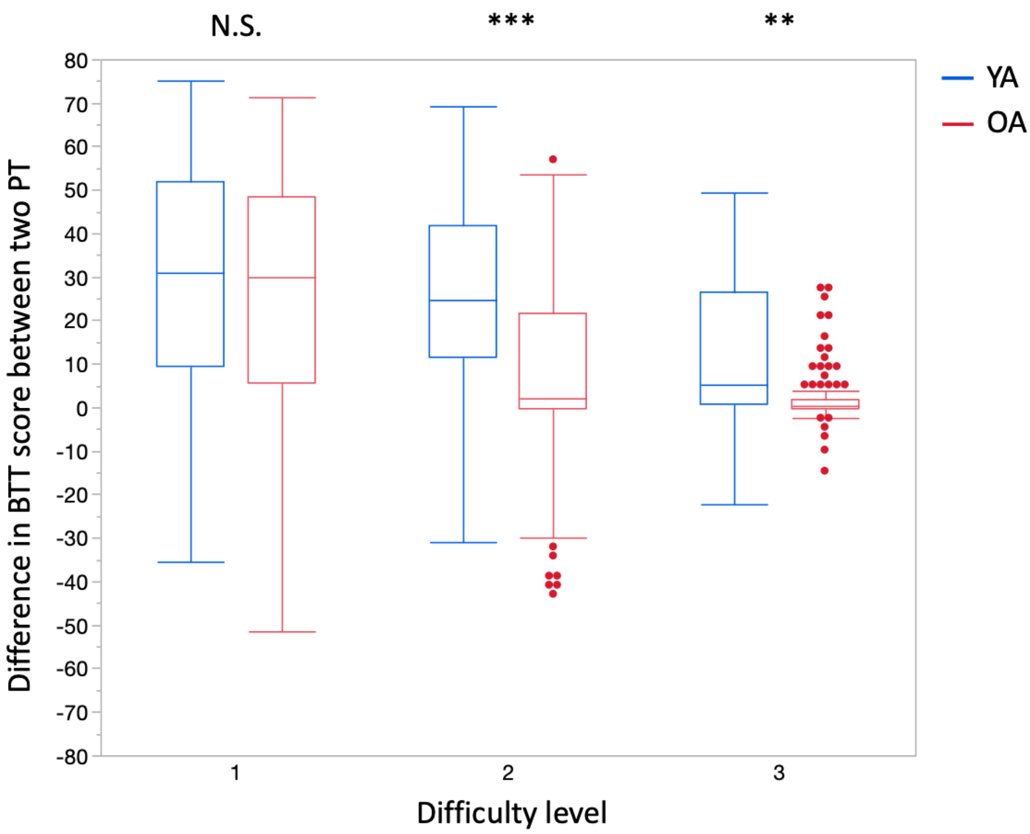
DL	Age Group	M	SE	95% CI	MD	SE	P-value*
1	YA	33.743	2.461	[28.863 - 38.623]	-3.295	3.400	.928
	OA	37.038	2.346	[32.386 - 41.691]			
2	YA	34.070	2.325	[29.443 - 38.696]	16.966	3.186	< .001
	OA	17.103	2.179	[12.766 - 21.441]			
3	YA	25.116	2.505	[20.150 - 30.082]	20.409	3.432	< .001
	OA	4.707	2.346	[0.054 - 9.359]			

Note. The mean improvement in BTT score between progression tests one and three, which represents bimanual motor learning ability between those two progression tests, was reported per difficulty level for each age group. PT: progression test; DL: difficulty level; YA: younger adults; OA: older adults; M: mean increase in BTT score between progression test one and three; SE: standard error; %: percentage; CI: confidence interval; MD: mean difference in bimanual motor learning ability between younger and older adults for a certain difficulty level.

* p < .017

Figure 6

Bimanual Motor Learning Ability per Difficulty Level for Younger and Older Adults for PT 2-1

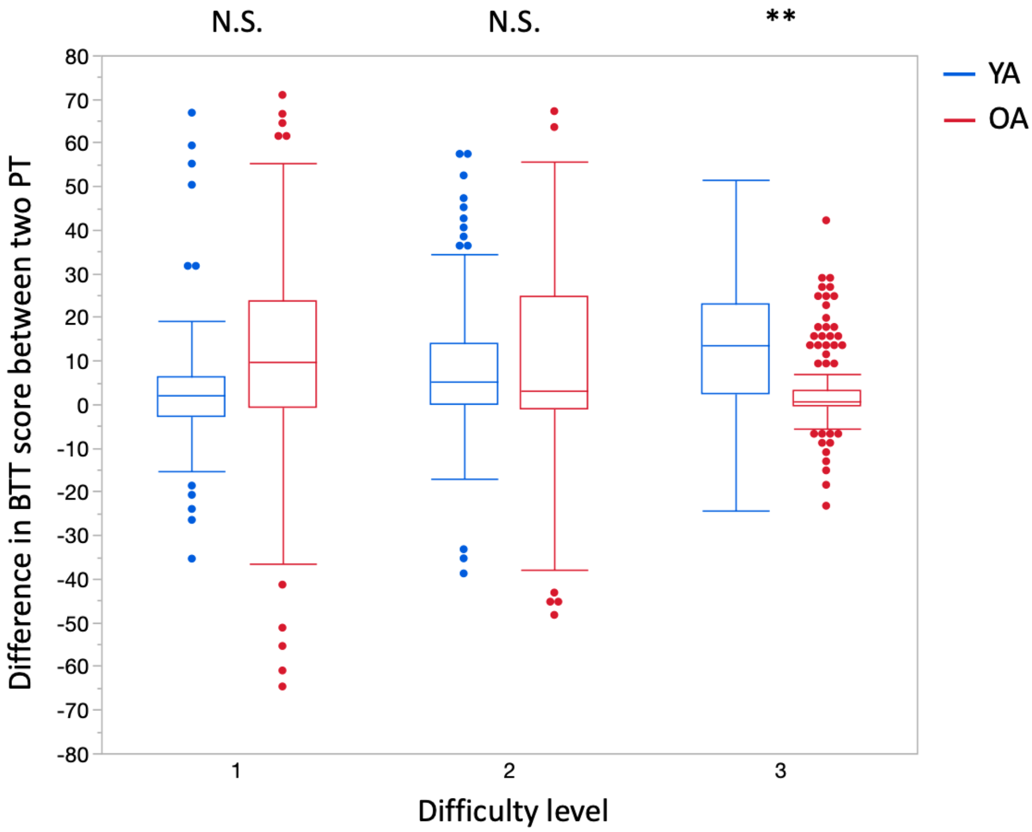


Note. The box plots visualize the bimanual motor learning ability between progression tests one and two, represented by the difference in BTT score between these two progression tests, per difficulty level for younger and older adults. The raw data was added in the form of dots. BTT: bimanual tracking task; PT: progression test; YA: younger adults; OA: older adults.

N.S.: nonsignificant difference between younger and older adults at a significance level of .017; **: significant difference between younger and older adults at a significance level of .017 with $p < .01$; ***: significant difference between younger and older adults at a significance level of .017 with $p < .001$.

Figure 7

Bimanual Motor Learning Ability per Difficulty Level for Younger and Older Adults for PT 3-2

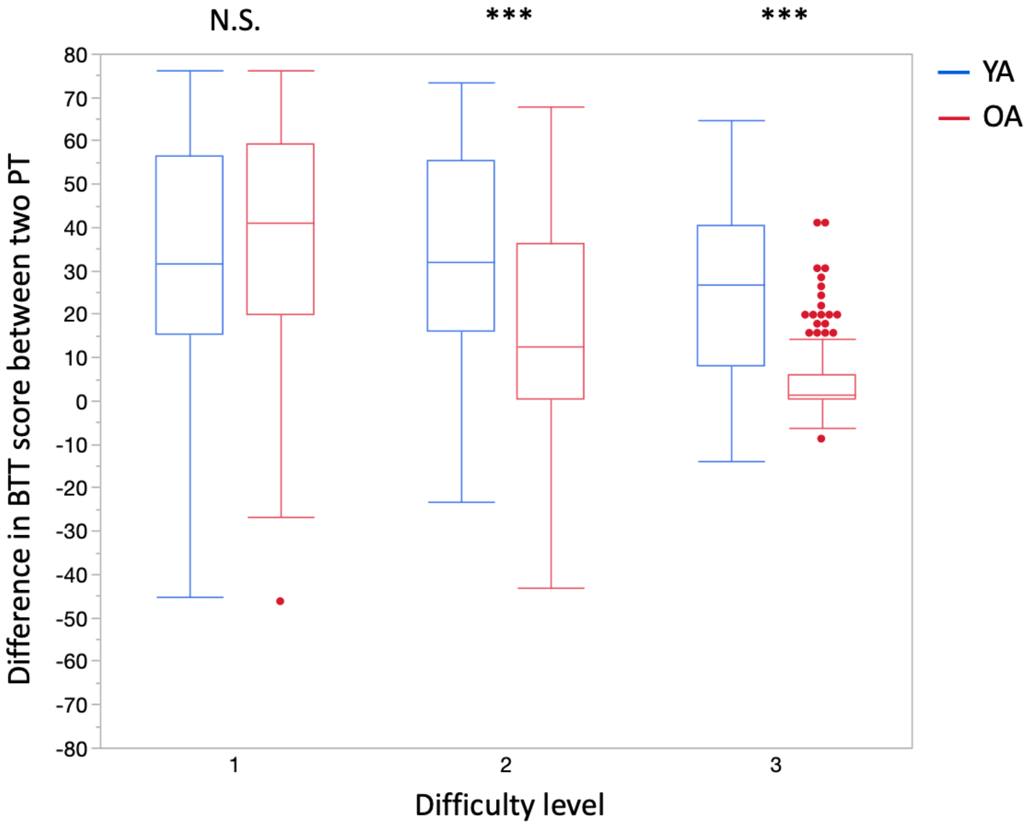


Note. The box plots visualize the bimanual motor learning ability between progression tests two and three, represented by the difference in BTT score between these two progression tests, per difficulty level for younger and older adults. The raw data was added in the form of dots. BTT: bimanual tracking task; PT: progression test; YA: younger adults; OA: older adults.

N.S.: nonsignificant difference between younger and older adults at a significance level of .017; **: significant difference between younger and older adults at a significance level of .017 with $p < .01$; ***: significant difference between younger and older adults at a significance level of .017 with $p < .001$.

Figure 8

Bimanual Motor Learning Ability per Difficulty Level for Younger and Older Adults for PT 3-1

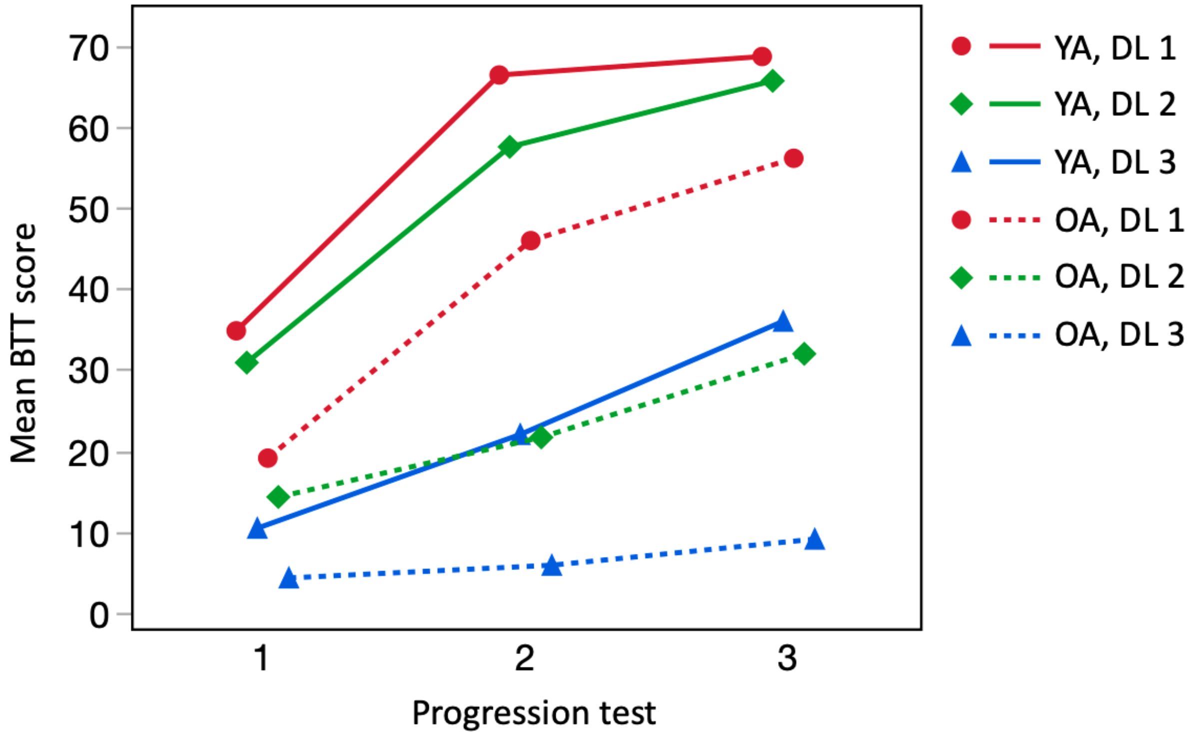


Note. The box plots visualize the bimanual motor learning ability between progression tests one and three, represented by the difference in BTT score between these two progression tests, per difficulty level for younger and older adults. The raw data was added in the form of dots. BTT: bimanual tracking task; PT: progression test; YA: younger adults; OA: older adults.

N.S.: nonsignificant difference between younger and older adults at a significance level of .017; **: significant difference between younger and older adults at a significance level of .017 with $p < .01$; ***: significant difference between younger and older adults at a significance level of .017 with $p < .001$.

Figure 9

Influence of Task Difficulty on the Relationship Between Aging and Bimanual Motor Learning



Note. The mean BTT scores per progression test were visualized per difficulty level for younger and older adults. The slope of the line between the mean BTT scores of two progression tests represents the bimanual motor learning ability between those two progression tests for a certain difficulty level and age group. BTT: bimanual tracking task; YA: younger adults; OA: older adults; DL: difficulty level.

4. Discussion

4.1 Influence of aging on bimanual motor performance

The results show a significant difference in bimanual motor performance between YA and OA, with YA outperforming OA on the BTT. These findings support the hypothesis that bimanual motor performance will decrease as a result of aging and are in line with previous literature (Monteiro et al., 2017; Maes et al., 2017; Van Hoornweder et al., 2022; Bhakuni & Mutha, 2015; Bangert et al., 2010; Boyke et al., 2008; Leinen et al., 2016; Moes et al., 1995; Pauwels et al., 2015; Serbruyns et al., 2013; Solesio-Jofre et al., 2014; Spirduso & Choi, 1993; Stelmach et al., 1988; Voelcker-Rehage & Willimczik, 2006). However, the results are not in line with the study of Summers et al. (2010), which stated there were no differences in motor performance between YA and OA in continuous bimanual tasks.

Several mechanisms described in the current literature could explain the negative impact of aging on bimanual motor performance. The following list of explanations is non-exhaustive and focuses on mechanisms in the brain.

First of all, high-level areas of the brain become more vulnerable to degeneration while aging, which causes a substantial decrease in motor performance as one gets older (Ren et al., 2012). Additionally, degeneration of the neuromuscular system that comes with aging results in deteriorated muscle coordination in bimanual tasks (Jin et al., 2019). Supporting this, several included studies of Maes et al. (2017) stated that grey and white matter decline in volume and microstructural properties due to aging, which is associated with poorer bimanual motor performance. Additionally, aging is associated with cortical thinning in most brain regions (MacDonald et al., 2021; Sowell et al., 2004). Reduced motor performance has been linked to these age-related degenerative changes, which are a typical part of aging (Blinkouskaya et al., 2021; Fjell & Walhovd, 2010; Seidler et al., 2010).

Secondly, the interhemispheric communication through the corpus callosum can play an important role in the effect of aging on bimanual motor performance. It is responsible for the temporal coupling of simultaneous movements of the hands or fingers during continuous tasks (Helmuth & Ivry, 1996; Ivry & Hazeltine, 1999; Kennerley et al., 2002). Serbruyns et al. (2013) stated that age-related detrimental changes in the microstructural organization of the corpus callosum can explain declines in bimanual motor performance associated with normal aging. More specifically, degeneration of the premotor, primary motor, primary sensory or occipital subregion of the corpus callosum is related to a decrease in bimanual motor performance (Serbruyns et al., 2013). Within the corpus callosum, there is a trend of frontal to dorsal age-related degeneration, so therefore the premotor subregion of the corpus callosum is most likely to be affected first (Abe et al., 2002; Bennett et al., 2010; Bhagat & Beaulieu, 2004; Burzynska et al., 2010; Camara et al., 2007; Coxon et al., 2012; Davis et al., 2009; Hofer & Frahm, 2006; Hugenschmidt et al., 2008; Madden et al., 2012; Ota et al., 2006; Raz & Rodrigue, 2006; Salat et al., 2005; Sisti et al., 2012; Sullivan et al., 2006; Sullivan & Pfefferbaum, 2006; Voineskos et al., 2012; Zahr et al., 2009).

A third mechanism that can explain the age-related declines in bimanual motor performance is cortical hyperactivity, which is widespread increased brain activity seen in OA compared to YA. Several studies have revealed regional hyperactivations in cognitive, perceptual, and motor circuits in OA (Cabeza, 2001; Cabeza et al., 2002; Calautti et al., 2001; Grady et al., 1994; Heuninckx et al., 2008; Li & Lindenberger, 1999; Logan et al., 2002; Mattay et al., 2002; Naccarato et al., 2006; Park et al., 2004; Riecker et al., 2006; Sala-Llonch et al., 2015; Van Impe et al., 2011; Ward & Frackowiak, 2003). The dedifferentiation hypothesis states that reduced inhibitory processes, indicating the cortical hyperactivity mentioned above, can cause a lower motor performance in OA (Grady et al., 1994; Li & Lindenberger, 1999; Logan et al., 2002; Park et al., 2004; Sala-Llonch et al., 2015). Neural dedifferentiation implies that the allocation of neural resources is impaired, which compromises the accuracy of cortical representations and neural processes (Koen & Rugg, 2019). "Many factors likely contribute to age-related neural dedifferentiation, including age differences in neuromodulatory drive, the efficacy of inhibitory neurotransmission, response to task demands, and cumulative life experience.” (Koen & Rugg, 2019)

So in conclusion, the negative impact of aging on bimanual motor performance can possibly be explained by aging-induced neural degeneration, impairment of the corpus callosum and cortical hyperactivity.

4.2 Relationship between aging and bimanual motor learning

The data revealed a significant effect of aging on bimanual motor learning in favor of the YA when comparing PT two to PT one and PT three to PT one. These findings do support the hypothesis that stated YA learn bimanual tasks at a higher rate than OA and are in line with previous literature (Perrot & Bertsch, 2007; Ren et al., 2012) However, no significant effect of aging on bimanual motor learning was found when comparing PT three to PT two, i.e. comparable bimanual motor learning rate between YA and OA. These findings, on the other hand, do not support the hypothesis mentioned above, but they are in line with other previous literature (Bhakuni & Mutha, 2015; Hoff et al., 2015; Voelcker-Rehage & Willimczik, 2006). Different from the findings of this dissertation, Monteiro et al. (2017) found that OA had a higher bimanual motor learning rate than YA and Adab et al. (2018) stated that OA learned at a higher rate than YA during the early stages of bimanual motor learning, while YA learned faster during the later stages of bimanual motor learning. The results of this dissertation will be discussed in more detail below.

The difference in bimanual motor learning between YA and OA that was found when comparing PT one and three is mainly due to the difference in bimanual motor learning between YA and OA when comparing PT one and two, since aging has no effect on bimanual motor learning when comparing PT two and three. Possible explanations for this significantly larger improvement in bimanual motor performance in YA than in OA, when comparing PT one to two, will be listed below. First of all, when learning a bimanual task, OA showed a lower level of neural plasticity (Rueda-Delgado et al., 2019), which is the ability of the brain to modify its structures and functions in response to specific stimuli or environmental exposure. Since learning is believed to depend on neuroplasticity, the lower level of neuroplasticity may contribute to the observed difference in bimanual motor learning between age groups. (Pascual-Leone et al., 2011; Ramón & Cajal, 1904). Furthermore, just as in motor performance, aging-related cortical thinning in most brain regions (MacDonald et al., 2021; Sowell et al., 2004) can cause difficulties in motor skill learning (Blinkouskaya et al., 2021; Fjell & Walhovd, 2010; Seidler et al., 2010). Another explanatory mechanism is the fact that the risk of damage or degeneration in high-level areas of the brain increases as one gets older, which causes a reduced motor learning rate in OA (Ren et al., 2012).

The fact that there was no significant effect of aging on bimanual motor learning in the later stage of the training, between PT two and three, can possibly be explained by the following studies. One explanation might be the poorer motor performance on PT two of the OA in comparison to the YA. According to Monteiro et al. (2017), this lower baseline motor performance level in OA is likely to cause a higher improvement in motor performance in this age group compared to YA. Furthermore, Maes et al. (2017) stated that YA have a higher initial motor performance, which was also found in this study, and therefore a ceiling effect can appear sooner. For that reason, the comparison of changes in bimanual motor performance between YA and OA should be made with caution.

So in conclusion, the negative impact of aging on bimanual motor learning, which was observed in early stages of bimanual motor learning, can possibly be explained by the age-related decrease in neural plasticity, cortical thinning and increased risk of damage or degeneration in high-level areas of the brain. Additionally, the comparable bimanual motor learning rate between YA and OA in later stages of bimanual motor learning can be explained by the lower motor performance level of OA, which can cause a higher improvement in motor performance, or by the possible ceiling effect in YA because they have a higher initial motor performance.

4.3 Influence of task difficulty on age-related changes in bimanual motor learning

The data showed a significant effect of task difficulty on age-related changes in bimanual motor learning. This significant effect was found in all three PT comparisons. Moreover, the data seem to show that the negative effect of aging on bimanual motor learning increases as the bimanual task gets more difficult (Figure 8). This negative effect of aging implies lower bimanual motor learning ability in OA compared to YA. However, this trend in the data was not tested and so further research on this is needed. These results support our hypothesis that states that age-related effects on bimanual motor learning, which cause OA to learn at a significantly slower rate than YA, will be larger in more difficult tasks (Maes et al., 2017; Voelcker-Rehage, 2008). Interestingly, Zvornik et al. (2024) observed that task complexity did not interact with bimanual motor learning for YA and OA. These contradictory findings point out the need for more research.

Within continuous movements, in-phase movements are less complex than anti-phase movements (Maes et al., 2017). Shih et al. (2019) describe in-phase movements as movements in which both hands move in a mirror-symmetrical pattern, relative to the midline of the body. This involves the simultaneous recruitment of bilateral homologous muscle units. In contrast, during anti-phase movements, homologous muscle groups are activated alternately. Additionally, when a task can’t be mastered within one session or when it has more than one degree of freedom, Wulf and Shea (2002) address it as complex.

Bootsma et al. (2021) provide a possible explanation for why task difficulty has an influence on the relationship between aging and bimanual motor learning, in which OA were disadvantaged as the gap in bimanual motor learning ability between YA and OA widened when the task got more difficult. The study stated that OA showed reduced neural plasticity compared to YA when performing a task with a high difficulty level, while this was not the case when performing a task with a low difficulty level (Bootsma et al., 2021). As explained before, neural plasticity plays an important role in motor learning (Pascual-Leone et al., 2011; Ramón & Cajal, 1904).

4.4 Shortcomings of the study

There are several shortcomings of this study. First of all, the time interval between PT could differ between participants, which possibly influenced the achieved score on the second or third PT. Also, there was no control group of YA and OA in this study. Control groups can be an added value because then you can better exclude the influence of other factors. Therefore, the effects observed in this study may be caused by factors other than aging alone, such as motivation, physical activity level or genetics. Furthermore, in five participants, one or more BTT scores are missing because something went wrong during data collection. The missing BTT scores were spread over the three PT. These missing data can have an effect on the calculation of the differences in BTT score between two PT. To look at the effect of this missing data, the data analyses were repeated without the participants for whom some data were missing. The conclusions that could be drawn from these results were the same as those based on the original results. This suggests that the missing data does not have a major effect on the findings of this dissertation. Besides, due to technical issues, some participants performed several trials twice during the PT. In the group of YA, this was the case for three participants and in OA this was the case for two participants. Another limitation concerns potential selection bias, as participation in this study was voluntary. According to The Cochrane Collaboration (2008), selection bias indicates systematic differences in the baseline characteristics between the study population and target population, which is the overall population for which the measure of effect is being calculated and from which study members are selected (Alexander et al., 2001). Participants who volunteer for a study may have different characteristics from the average person in the target population. The baseline features of people who do not reply to requests to participate in a study are typically different from those of responders. As a result of selection bias, the final study population may not be representative of the target population (Alexander et al., 2001). Furthermore, performance on PT one actually already has a small learning component in it, because the participants already performed the BTT in the mock MRI and during the fMRI. This makes it difficult to make an assessment of pure motor performance without motor learning. Additionally, the BTT training was progressive and individualized because the BTT conditions and therefore the difficulty level depended on the motor performance of the participant on previous BTT trials. This approach can be seen as a disadvantage because some participants got the chance to train BTT trials with a high task difficulty before performing the PT, while other participants did not. A last shortcoming of this study is the subjective way of evaluating the possible impact of medication on motor performance and/or motor learning.

4.5 Future research

Concerning research question one, a suggestion for future research is to explore possible interventions that could minimize the negative effects of aging on bimanual motor performance. Mainly, interventions that focus on aging-induced neural degeneration, impairment of the corpus callosum and cortical hyperactivity should be investigated. Concerning research question two, further research should explore why the effect of aging on bimanual motor learning is not the same throughout the whole training period. Also, possible explanations for this influence of the stages of motor learning should be investigated. Furthermore, since this dissertation focused on an experimental task, future research should investigate how aging affects everyday bimanual motor tasks, such as playing an instrument. Additionally, the influence of aging on bimanual motor learning should be investigated again, but this time with a control group for both age groups, so the influence of other factors can be negated. Both control groups should be similar to the intervention groups. Ideally, they should have the same gender distribution and the same mean and standard deviation of age. Concerning research question three, it is necessary to further investigate the influence of task difficulty on the relationship between aging and bimanual motor learning, since current evidence on this matter is still very limited. Also, possible explanations concerning this influence of task difficulty need to be investigated. Another suggestion for future research is to further differentiate between different possible components of task difficulty, for example asymmetry of the hands. Lastly, future research should further investigate the underlying neural mechanisms that contribute to the increasing gap in bimanual motor learning between YA and OA as task difficulty increases, with OA being disadvantaged.

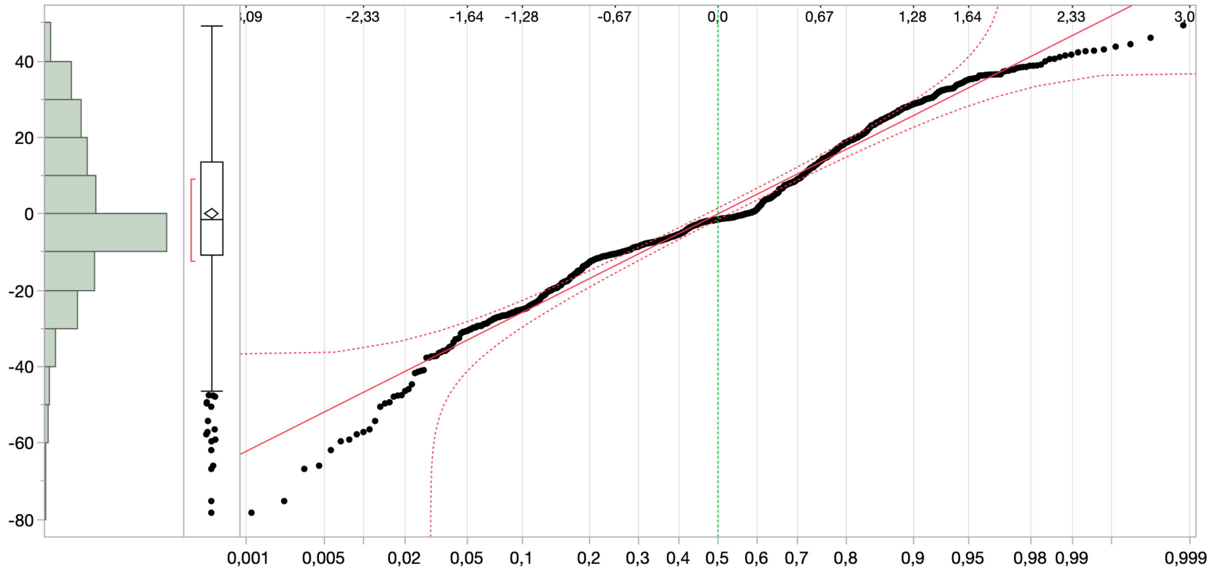
5. Conclusion

In conclusion, aging causes a decrease in bimanual motor performance. Furthermore, aging has different effects on bimanual motor learning in different stages of learning, with a negative effect of aging found in the early stages of learning and no significant effect of aging in later stages of learning. The bimanual motor learning gap between YA and OA becomes larger as task difficulty increases, with OA being disadvantaged.

6. Attachments

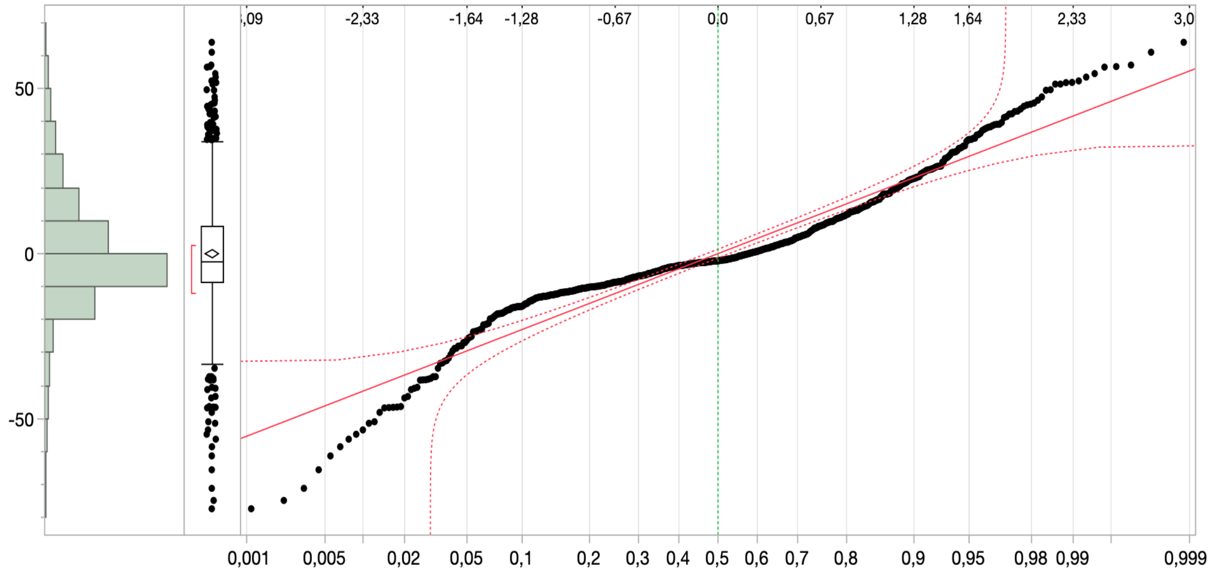
Attachment 1

Normal Quantile Plot for PT 2-1



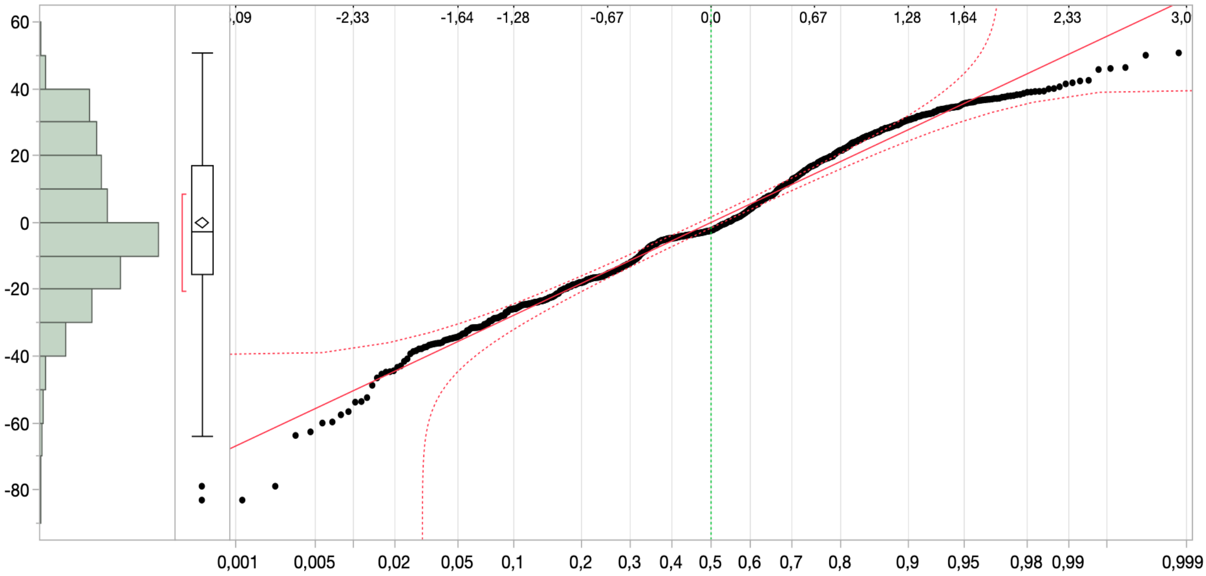
Attachment 2

Normal Quantile Plot for PT 3-2



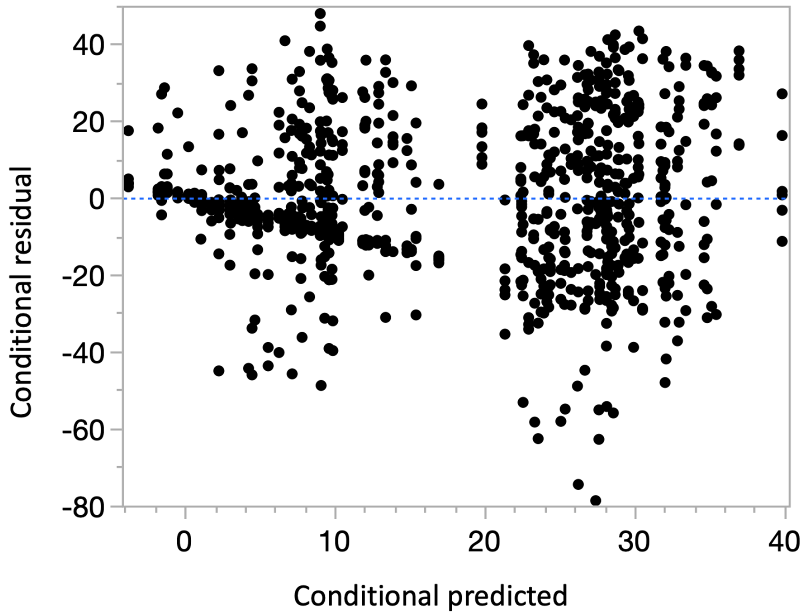
Attachment 3

Normal Quantile Plot for PT 3-1



Attachment 4

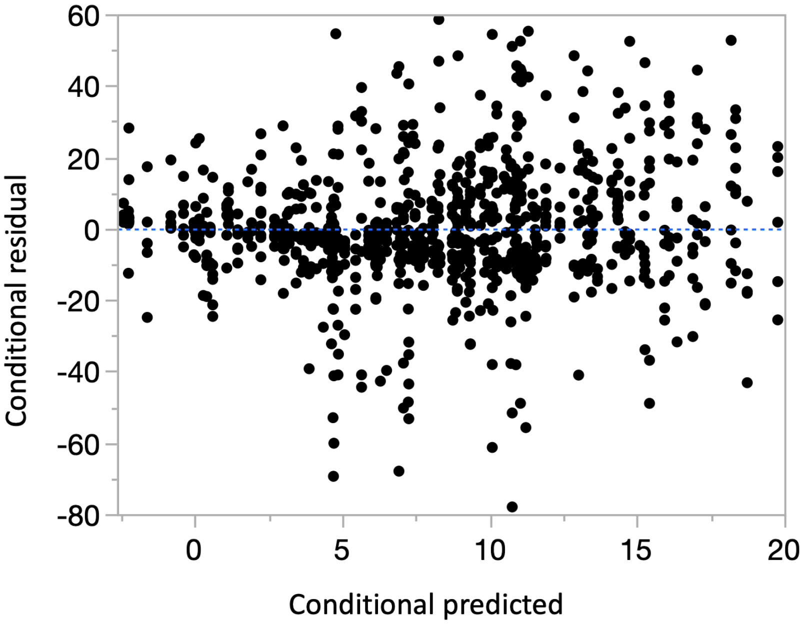
Conditional Residual by Predicted Plot for PT 2-1



x

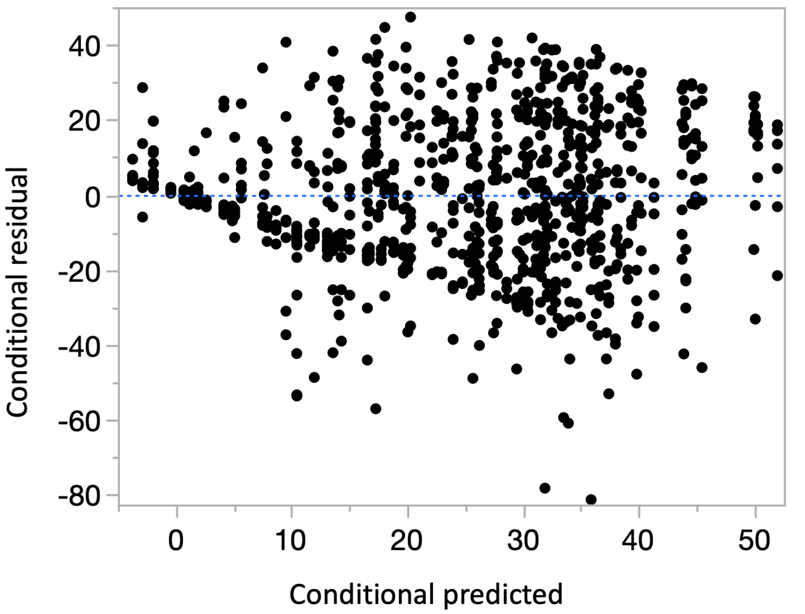
Attachment 5

Conditional Residual by Predicted Plot for PT 3-2



Attachment 6

Conditional Residual by Predicted Plot for PT 3-1



7. Reference list

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