Sex- and Experience-Related Differences in Bimanual Coordination Development

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ABSTRACT

Sex- and experience-related differences in bimanual coordination have been found previously but are often reported separately. Here, we characterize visuomotor skill performance in relation to age, sex, and athletic experience in order to indirectly gain insight into the neural processes that underlie this advanced level of eye-hand coordination. We use a novel precision bimanual task composed of a modified washer-peg board. We recruited three age and two experience groups (9-10, 11-12 and 13-15, elite versus house league). We also developed a Whole-hand bimanual task in order to account for any manual dexterity discrepancies. The results show that the effect of skill and sex are not seen until later years developmentally, at that point there is a strong effect of sex on bimanual coordination. Future research that aims to look at the development of motor skills and control should also look at sex and experience effects.

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LIST OF ABBREVIATIONS

ACC – Anterior Corpus Callosum

CC – Corpus Callosum

CMA – Cingulate Motor Area

DTI – Diffusion Tensor Imaging

EEG – Electroencephalography

FA – Fractional Anisotropy

MRI – Magnetic Resonance Imaging

PCC – Posterior Corpus Callosum

PPC – Posterior Parietal Cortex

PPT – Perdue Pegboard Test

SMA – Supplementary Motor Area

Introduction

Whether one is lifting a box above one's head, holding a container to remove the lid, or buttoning up a shirt, most bimanual tasks are done with ease. In humans, asymmetric bimanual coordination is first seen at 10-12 months of age (Fagard & Peze, 1997). However, those at 1 year of age often relapse to mirror bimanual movements (Fagard & Peze, 1997). This type of coordination is not fully understood, especially when it comes to understanding how it is developed. An abundance of research has been conducted on young or older adults but little research has been carried out with adolescents. When looking at motor development in the pubertal years, one must acknowledge the importance of quantifying any sex differences that may occur. Another important factor is personal history, more specifically, athletic exposure and experience. Performing coordinated movements in a given sport is commonly attributed to years of systematic training. Generally, elite level athletes spend a greater amount of hours training resulting in a high degree of athletic experience, when compared to recreational athletes. To date, the model 'experienced' population that has been typically used in the bimanual coordination literature uses musicians (Fujii, Kudo, Ohtsuki, & Oda, 2010; Fujii & Oda, 2009). Their years of dedication to skilled bimanual performance have been shown to not only lead to functional differences, but also structural brain differences (Fujii, Kudo, Ohtsuki, & Oda, 2010; Fujii & Oda, 2009). To our knowledge, however, research has still not looked comprehensively at the effects of both biological sex and athletic experience effects on the normal development of bimanual coordination.

Previous Studies of Bimanual Coordination and Related Brain Changes

It is difficult to compare findings across the bimanual coordination literature because each study tends to use different bimanual tasks. The selected task can greatly influence one's results. There are a few different general categories of bimanual tasks. First, in-phase or symmetrical (de Boer, Peper & Beek, 2012) tasks require the use of homologous muscles (ex. hands clapping). Anti-phase or asymmetrical tasks are those in which the action is produced by non-homologous muscles such as doing wrist flexion on one hand while the other is doing extension (de Boer et al., 2012). The term asymmetrical can also be used to describe more complicated movements, whereby each hand has an independent task but both work together for a common goal (Otte & van Mier, 2006). Lastly, there are independent bimanual movements where each limb has an independent task (Otte & van Mier, 2006). An example of this would be one hand drawing a circle while the other hand draws a square. The level of difficulty increases when moving from in-phase to independent. It has been suggested the two most stable types of tasks are in-phase followed by anti-phase, meaning that in order to perform these tasks there is not a great deal of procedural learning that needs to occur (Zanone & Kelso, 1992; Swinnen et al., 1998). There are other aspects of a bimanual task that can also affect the difficulty, such as timing (temporal) and location of targets (spatial).

Aside from understanding where a bimanual task falls on the large spectrum, it is equally important to specify if participants are given time to train and learn the task or if it is a novel task. Andres et al. (1999) used both unimanual and bimanual tasks and recorded neural activity using electroencephalography (EEG). They recorded before and during skill acquisition using various combinations of finger tapping sequences. The authors observed that there was a significantly greater amount of coherency in the frontocentral mesial cortex when learning the bimanual task relative to when learning the unimanual task. Once the 30 minutes of training was completed, the level of coherence had decrease to similar to those levels seen when performing novel or learnt unimanual tasks. The reduction in coherence was also observed in the parietal and frontal areas. It was concluded that interhemispheric communication during bimanual task learning depends on the intact callosal connections. This finding was further supported by magnetic resonance imaging (MRI) studies (Sun, Miller, Rao & D'Eposito, 2007). Sun et al. (2007) contrasted early versus late learning of a new bimanual sequence, showing greater activation in the primary somatosensory area. The specific cortical areas that exhibit a decrease with training were superior parietal cortex, right dorsal premotor cortex, right dorsolateral prefrontal cortex, right ventral premotor cortex and left cerebellar (Debaere, Wenderoth, Sunaert, Hecke & Swinnen, 2003). Figure 1 shows the amount of decreased activation at the end of training in the superior parietal cortex (Debaere et al., 2003). In the these two studies, a novel task was given and the results showed that there had been some learning that was reflected in changes in the activation of the brain's cortex. A follow up study sought to test for further changes in brain activation when training was continued after having learnt the task (Puttemans, Wenderoth & Swinnen, 2005). Automatization (thorough learning with only minimal use of on-line feedback to monitor performance) is something that we would expect to see in more experienced musicians or elite athletes. We know that when a skill is acquired, such as a bimanual task, that the supplementary motor area (SMA) and cingulate motor area (CMA) show greater activation. In a study conducted by Puttemans et al. (2005), bimanual performance was stable with significantly reduced errors from training commencement, but the authors wished to see if they could push training further and document associated brain changes. The participants continued to train with the addition of a dual-task. To show that learning occurred as in previous

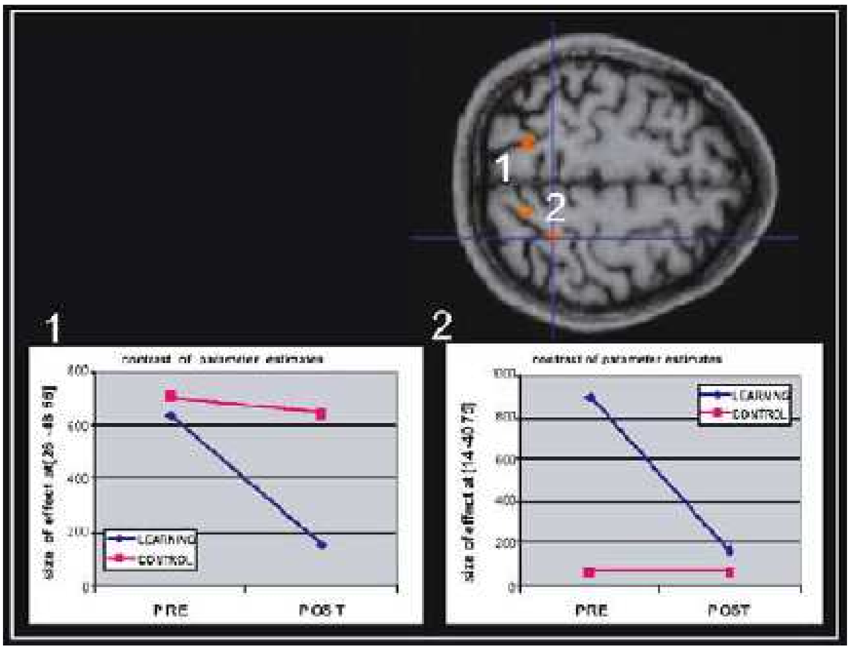

Figure 1. Brain activity associated with motor learning. Note decrease in IPS activation displayed in bottom right graph (adapted from Debaere et al., 2003).

studies, they saw a decrease in ventral and dorsal premotor area, right supramarginal gyrus and ventrolateral prefrontal cortex. When scanned after the automatization of the task, there was a decrease in SMA activation (SMA-proper). The authors concluded that there was a decreased necessity to inhibit pre-existing movement tendencies. Also at this stage of skill there is a feedforward-driven execution mode.

The Corpus Callosum and Bimanual Coordination

The corpus callosum (CC) is a structure that connects the two hemispheres together. As such, it plays an important role in bimanual coordination and has been the focus of much study. Before performing analyses of coordination development or looking for differences across groups, the CC is often divided into the regions shown in Figure 2. The size of the CC will depend on size and amount of axons, packing density, degree of myelination, vasculature and extravascular fluid (Giedd et al., 1996).

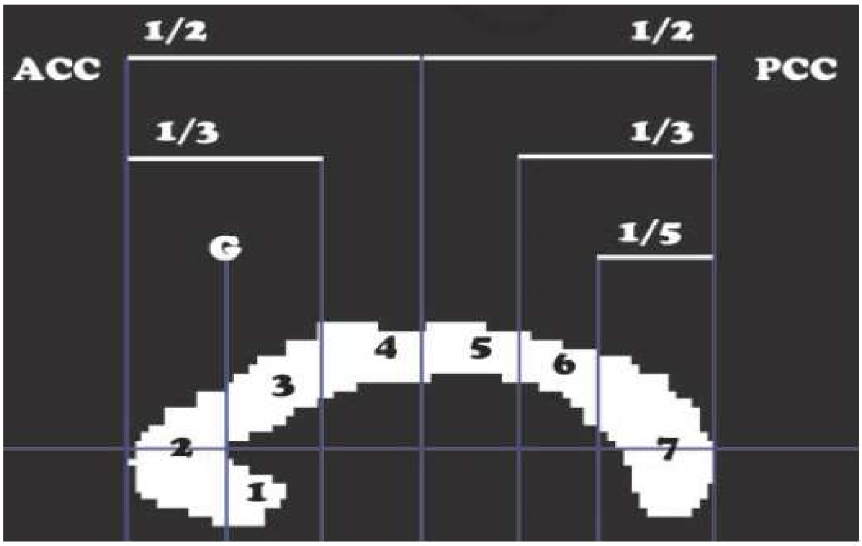

Figure 2. Midsagital view of the corpus callosum, anterior corpus callosum (ACC) and posterior corpus callosum (PCC). 1. Rostrum, 2. Genu, 3. Rostral Body, 4. Anterior Midbody, 5. Posterior Midbody, 6. Isthmus, and 7. Splenium. (Fling et al., 2011)

Thompson and colleges (2000) performed a magnetic resonance imaging (MRI) study looking at the myelination of the CC from ages 6 to 15 years old. The tem "rostro-caudal wave" was coined to describe these peak myelination results. During the younger years there is a greater rate of myelination in the rostral part of the CC. Followed by a peaking of the caudal CC (isthmus and splenium) myelination around 11 to 15 years of age. Other research was done with an age range of 4 to 18 years of age, with similar results (Giedd et al., 1996). This latter study noticed that when looking at the size of the CC across their age range there was a large increase in size

(Giedd et al., 1996). However, once they separated the rostral from the caudal portions they noticed that there was very little development in the rostral potion of the CC and that the age increase in the CC as a whole was being driven by the caudal portion development (Giedd et al., 1996). These findings suggested that the rostral portion of the CC reaches adult size very early (Giedd et al., 1996). Notably, the caudal portion of the CC, or more specifically the splenium, was larger and more bulbous in females (Figure 3B) (Allen, Richey, Chai & Gorski, 1991). Although they found an apparent sex difference in children, the sex difference was more obvious in the adult group (Allen et al., 1991). In particular, these authors observed a drastic increase in CC growth which plateaued nearing the second decade of life.

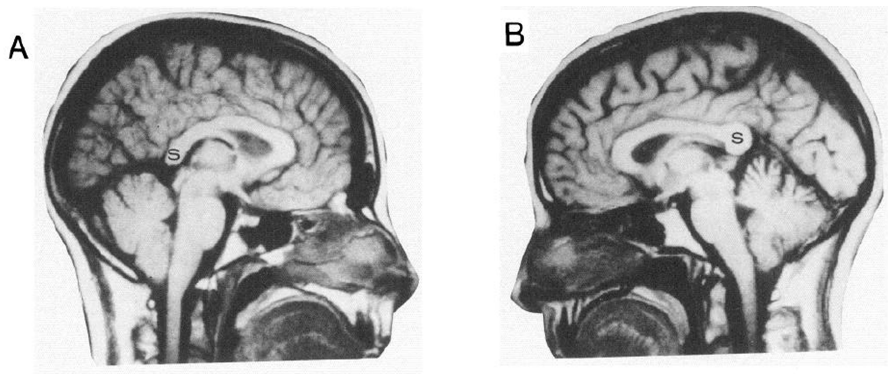

Figure 3. Midsaggital view of the brain showing the different size and shape of the splenium. A. Male B. Female (Allen et al. 1991)

As discussed above with the studies on bimanual task learning, one must rely heavily on regions of the parietal cortex initially, but then these areas become less active when there has been some training. With a larger splenium there could be a potential for females to have better inter-hemispheric communication when learning. The findings from Thompson et al. (2000)

demonstrate that girls, ages 6 to 15, tend to develop the posterior portion of the CC at an earlier age than boys. Having a larger splenium and also having this area myelinated at an earlier age could suggest a female advantage for the learning and performance of bimanual skills. Aside from looking at the CC size, there are other ways to examine the CC. Using Diffusion Tensor Imaging (DTI), one can look at the integrity of white matter tracts, a measure called “fractional anisotropy” (FA). An increase FA is related to greater integrity of white matter tracts that is, a “stronger connection” for information to travel from one brain area to another. Looking at the FA in the posterior cortical regions, Heidi Johansen-Berg and her colleagues used DTI to address the question if having an increased FA in the white matter tracts in the CC resulted in increased bimanual abilities (Johansen-Berg, Della-Maggiore, Behrens, Smith & Pause, 2007). The participants were to perform an asymmetric task and were scanned. Their bimanual performance was then correlated to FA data. Using a region of interest at the midbody of the CC, they found connections to the SMA and the CMA. As expected those that had a greater FA showed enhanced bimanual performance.

Lastly, much has been learnt about the relationship between bimanual coordination and the CC from callosotomy studies. Persons that undergo the resection of the CC often do so as a treatment for intractable epilepsy (Kennetly et al., 2002). In one study, persons that were about to undergo callosotomy were recruited for a bimanual coordination experiment. They were asked to perform an asymmetrical drawing task that was done pre-surgery, post-anterior callosotomy, and post-posterior callosotomy (Eliassen et al., 1999). Pre-surgery and post-anterior callosotomy performed similarly on the task. However, this was not true for the post-posterior callosotomy (PPC), whose performance deteriorated markedly following surgery. The author’s , conclusion was that the PCC is more important for spatial abilities, and that tasks such as asymmetrical or independent bimanual tasks would be challenging for these patients.

Normal Bimanual Development

The development of asymmetrical bimanual coordination is first seen in infants of 7 to months old, and use of both hands continues to become more frequent with age (Fagard & Peze, 1997). In a study of infant coordination, Fargard and Peze (1997) used three unique objects that required the infant to use both hands with independent tasks for a common goal. An example was the tube in a container task. The infant was to hold the container with one hand and the other hand would reach inside and grab the tube. They tested infants over a number of months and noticed the greatest increase in performing this task using both hands was most evident at 10 months old. This use of a bimanual coordination strategy continued to increase in frequency until they concluded their study at 1 year of age. A second study looked at the development of bimanual coordination across a wider age range, 5 to 11 years of age (Barral et al., 2006). Researchers observed an increase in performance with age, with 11 year olds performing superiorly. They relate their findings to the development of the CC, suggesting that it is important to be able to inhibit movements across hemispheres in order to perform a parallel movement but also to perform with a faster reaction and movement time. The issue is not that 5 year olds cannot produce the movement, but that they are not done in an efficient and timely manner until full development of certain brain structures. One of their most notable findings was that performing independent hand movements was something that was last to develop in terms of being able to create a motor plan and initiate it. This seems to occur between the ages of 8 and 11 years of age. The authors concluded that although at 11 years of age children are able to initiate movements fast, their time to complete the movement is still not fully developed because of their decreased ability to receive feedback and make adjustments during movement. Along the same lines, Olivier et al. (2007) were trying to understand the development of reaching and grasping in a bimanual task (Olivier, Hay, Bard & Floury, 2007). They noticed that when performing a bimanual task there was a decrease in peak velocity compared to the unimanual movements in the younger children aged 6 – 11 years of age (Olivier et al., 2007). They observed that the 11 year olds had similar grasp aperture abilities, determined by the distance between the index finger and thumb, as the adults that participated. It appeared that all other ages would over-estimate the size of the object and have a larger aperture. Olivier and colleges (2007) believed that the over-correction seen in the younger group was due to their lack of tuned proprioception. These factors could conceivably strongly affect the performance for a bimanual task that included the act of reaching and grasping, let alone when trying to learn a new skill. In summary, based on the literature, children younger than 11 years of age have slower movement times and will over estimate the size of the object that will be grasped. This is not to say that 11 years olds have reached their plateau, there is still further development of this motor skill (Olivier et al., 2007).

Sex Differences in Bimanual Coordination

It is evident that there are sex differences in the CC which could change the development and performance of several motor outputs. The Nine-hole Peg Test is a standard bimanual task that is more focused on fine motor control. In the past, this test has revealed an age and sex affect (Poole, Burner & Torres, 2005). As expected, with an advancement of age children performed better, but interestingly females outperform males (Poole et al., 2005). When looking at manual dexterity the question that often comes up is the size of female hands compared to males. Peter and colleges (1990) addressed this issue using a Perdue peg board and found a female advantage until they had controlled for index finger and thumb differences. In contrast, there are other tests such as the Moberg pick-up test that demonstrate females having enhanced manual dexterity (Amirjani, Ashworth, Gordon, Edwards & Chan, 2007). Other theories that attempt to explain sex differences in motor coordination have proposed that males might be quicker in producing a single movement but when given a series of movements, females will be faster suggesting that females have the ability to cope with the rapid changes of position and programming speeds for motor tasks (Nicholson et al., 1996). Cohen, Poplin, Gold and Secular (2010) found that when given a series of hand gestures, females were able to learn faster and perform series of hand gestures with greater accuracy then males. The results could be attributed to the female advantage in motor planning (Cohen et al., 2010). Finally, a study looked at the spatial abilities of collegiate athletes in different sports (Lord & Garrison, 1998). They selected participants from a variety of sports and compared the performance on two tasks that were measures of spatial abilities (spatial visualization and spatial orientation) (Lord & Garrison, 1998). They found that females performed better at both of these tasks, although this varied when looking at each individual sport (Lord & Garrison, 1998). The authors acknowledged however that this conclusion was based on the use of only two spatial tasks and that further investigation should be done with a larger array of tasks (Lord & Garrison, 1998). Lord and Garrison (1998) reiterate the importance of understanding that sex differences exist and should be considered when attempting to makes comparisons of performance across sexes.

Experience Advantages in Bimanual Coordination

Aside from normal development of bimanual coordination it also important to look at factors that could influence development. For example, experience must play a role as seen in musicians who have spent years of deliberate practice, typically with instruments requiring coordination of both hands. A study conducted by Fujii and colleges (2010) compared the unimanual and bimanual performance of both professional drummers (determined by >13 years of practice) versus non-musicians. They found that in the unimanual task, non-musicians showed a greater difference between left hand and right hand performance when compared to musicians, which they believed was the reason for the musicians having a superior performance in the bimanual task. The authors speculating that an augmented symmetry of motor areas would allow for greater bimanual performance. A previous study by Fuji and Ode (2009) saw a correlation between years of experience and participants' performance on the bimanual task. With increased training they noticed more stable and rapid bimanual coordination. Using MRI data, it has been found that trained individuals have a more efficient brain activation compare to untrained when given a bimanual task (Janacek, Shah & Peters, 2000). Other studies that have used musicians and looked at the structural differences in the CC compared to controls (Schlaug, et al., 1995). Schlaug et al. (1995) found that the anterior portion of the CC was significantly larger when compared to both controls. When the authors compared early or late commencement of training, categorized by before or after the age of 7 years old, those that were classified as early beginner had larger anterior CC.

Purpose of the Present Study

Using an independent bimanual task, we aim to provide insight on two important factors, experience and sex, and how these factors can influence the development of bimanual coordination. One objective is to examine if one factor has a greater influence over the other, or whether there is a combination of both that can result in superior performance on the selected bimanual task. In a preliminary study, our laboratory has found that young female adults, ages 17 to 23, can outperform males in the selected bimanual task (McCullough et al. 2006).

Interestingly, the female advantage is further enhanced if they are elite level athletes. Due to the superior ability of elite level female athletes, we were motivated to examine at what point during development this enhanced performance is first noticeable. In order to examine these changes we undertook to analyse males and females near the time of adolescence. **Our hypothesis, based on previous findings and known brain differences, is that females will outperform males and that this difference will increase with age and experience.** These data will provide insight into how the development of bimanual coordination occurs. Taking a step further, it is of interest to see if development is enhanced, in terms of bimanual performance, when using elite study participants. The task used in a preliminary study required a certain amount of finger dexterity. Therefore we will also use an additional task that is similar to the initial task but without the high finger dexterity component, in order to differentiate this component between age and experience. We do not make any *a priori* assumptions about the relative influence of sex versus experience on coordination development, and leave this as an exploratory component of the present study.

Methods

The study design was separated by age groups 9-10, 11-12 and 13-15. Each group was further divided by sex and the level of experience (elite and non-elite). The classification of elite or non-elite was predetermined by the clubs and organization of the study participants. Non-elite groups participated at the house league level, which is more recreational that requires less amount of hours spent practicing skills. Elite level athletes are at a more competitive level and require some sort of skill assessment. Elite level athletes will often have team practice most days of the week. We collected data on 303 participants for the Precision bimanual task and 256 participants for the Whole-Hand bimanual task. Further information on group sizes is shown in

Tables 1 and 2. The age group separation is important to see how development occurs through puberty, a time that children are going through various physiological changes, not just in stature.

Table 1: Participant Groups for Precision Bimanual Task

	Boys		Girls	
	Non-Elite	Elite	Non-Elite	Elite
9 to 10	19	25	13	8
11 to 12	35	27	37	42
13 to 15	12	31	17	37

Table 2: Participant Groups for Whole-Hand Bimanual Task

	Boys		Girls	
	Non-Elite	Elite	Non-Elite	Elite
9 to 10	19	26	15	6
11 to 12	26	28	29	33
13 to 15	9	33	16	16

We recruited these athletes through contacting the leagues or coaches of various team sports (hockey, soccer, lacrosse, etc.). There was no bias towards one sport over others, this was part of a larger study and therefore a convenient sample. If there was interest from an organization then information of our study was sent to the coach to be distributed to the parents. In both bimanual tasks there was a greater percentage of our participants that played hockey

(Precision bimanual: 58.8% hockey, 29.6% soccer and 11.6% lacrosse, Whole-Hand bimanual: 62.3% hockey, 24.5% soccer and 13.2% lacrosse). We ensured that the consent form clearly states that participation in this study would not affect the parents' relationship with the league, team or coach.

Once we found teams that were interested in participating in the study we organized a day that we can meet them before a practice or game. Our device gave us the flexibility to go to any field or arena without the need for an electrical source. Once at the field/arena we met with the team and thoroughly explained the two tasks. Following a brief demonstration done by myself or a trained volunteer the study participants performed half of the task or until the participant felt comfortable, making this a novel task. Some took longer than others. We needed to ensure that all participants demonstrated an understanding of the tasks. The order of the two tasks was randomized to remove any learning effect.

Precision Bimanual Task

Along the end of the board closest to the study participant were a series of six pegs equally spaced. Each peg holds a larger washer (25mm diameter) sitting directly on top of a smaller washer (22mm diameter). This order was chosen to make it easier to grasp one washer at a time. There were two spring-loaded hinges that covered placement pegs for the washers located along the midline of the board. The first placement peg is located 18cm from the edge of the board, and the second placement peg is 31cm from the near edge of the board. The arrangement of the hinges is such so that the first hinge will only open when lifted towards the left and the second hinge opens towards the right. A digital timer with start and stop buttons is located to the left of the placement pegs.

Study participants began the trial with the index fingers of each hand touching the board immediately to the left and right of the six pegs. Study participants used the digital timer to start and stop their own trial located to the left of the pegs. This task required the study participants to lift a washer from a removal peg with their right hand, while lifting the spring-loaded hinge that is closest to them with the left hand to reveal a placement peg, and then to place the washer on the peg. The study participants were instructed to repeat the placement pattern, using the left hand to lift the next washer off the same removal peg while using the right hand to lift the

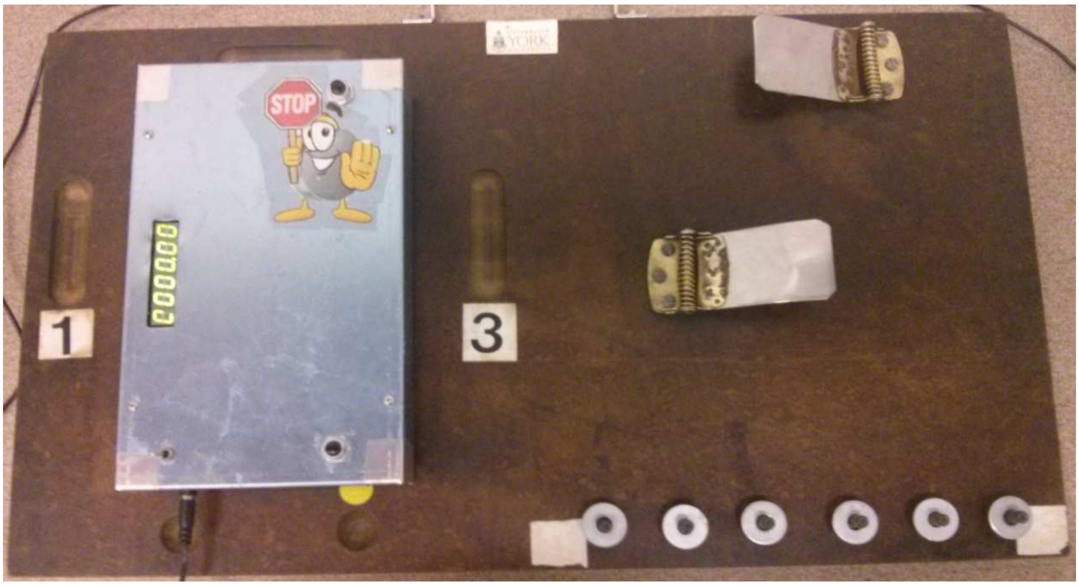

Figure 4. Precision bimanual task.

hinge furthest away from them, and continuing this sequencing until all twelve washers are sequentially placed on the six placement pegs. If the study participants performed an error in hand sequencing they were notified and corrected. In the case that a washer fell on the ground the test was terminated and restarted.

Whole-Hand Bimanual Task

This task is made to be identical to the washer layout. To replace washers there were two buttons at the edge closest to the subject. All buttons are the same size (20mm diameter). There are two spring-loaded hinges that cover each buttons. One located 18 cm and the other 30 cm from the edge closest to the study participant. The hinges are arranged so that the hinges will open out towards the sides of the board. The start button is located to the left. Once the trial is completed the timer will automatically stop.

The study participant was to press and hold a button, once this is released the timer began. The object is to first hit the right button with their right hand, at the same time lift the left hinge and press the button underneath with their right hand. This was to simulate one grabbing a washer from the peg and placing it under the hinge. This action was repeated but with left hand pressing the button closest to them and the right hand lifting the right hinge. Each sequence was carried out 6 times to simulate the placing of 12 washers. This was indicated by the lights illuminating at the bottom of the board. Once the last button is pressed the timer stops automatically. The board is programed so that button 1 is pressed before 2, if this order is not followed then it did not count as a completed cycle.

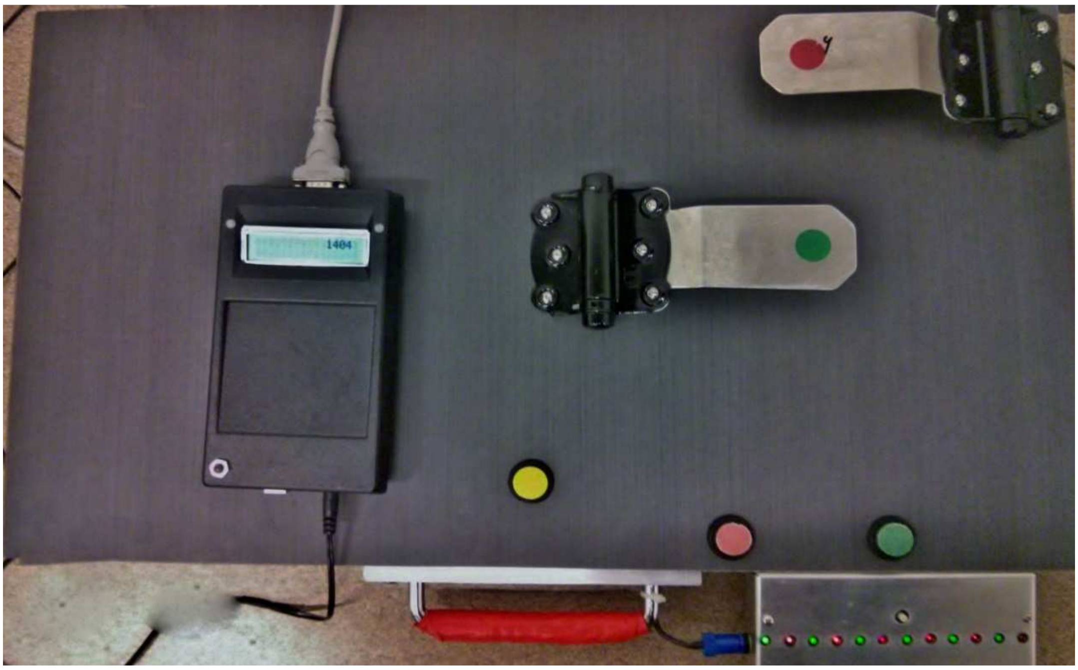

Figure 5. Whole-Hand bimanual task.

Data Analysis

The analysis was done using Kruskal-Wallis Test with IBM SPSS software. Post-hoc test will be performed using Bonferroni corrections.

Results

In this study we examined bimanual coordination in a large number of children over a range of ages and abilities. Overall, we observed differences in performance and variability as a function of our controlled factors (age, sex, and athletic experience level). For all of our data, we first applied a Levene's Test to determine the homogeneity of variance for both bimanual tasks.

The group variances were significantly different. Therefore we were unable to apply parametric methods to analyse these data, including analysis of variance (ANOVA). We thus used a Kruskal-Wallis Test for our timing analyses and a nonparametric test (Levene's) for our variance analyses.

Precision Bimanual Task

We observed that children ages 9 and 10 took significantly longer to perform the task when compared to the 11 to 12 age group ($n = 206$, $x^2 = 23.03$, $p < 0.001$) and the 13 to 15 age group ($n = 162$, $x^2 = 29.13$, $p < 0.001$) (Figure 6). However, there is no evidence that the 11 to 12 year olds performed more slowly than the 13 to 15 year olds ($n = 238$, $x^2 = 2.56$, $p > 0.05$). Interestingly, we observed an increase in performance for athletes that were participating in sports at an elite level ($n = 303$, $x^2 = 5.45$, $p < 0.05$) (Figure 7). Although increased performance is expected from elite level athletes, it was unexpected to see a training effect at such early ages. Also, we have selected a task that is not sport specific and yet we still see a clear relationship between skill and bimanual performance. As mentioned earlier, our group's previous work has found that females, ages 17 to 23, have an increased ability to perform more quickly on the Precision bimanual task relative to age-matched males. Here we find that this relationship still exists at younger ages as shown in figure 8 ($n = 303$, $x^2 = 34.67$, $p < 0.001$). However, we cannot conclude that females have superior bimanual abilities until we look at their performance on the whole-hand bimanual task.

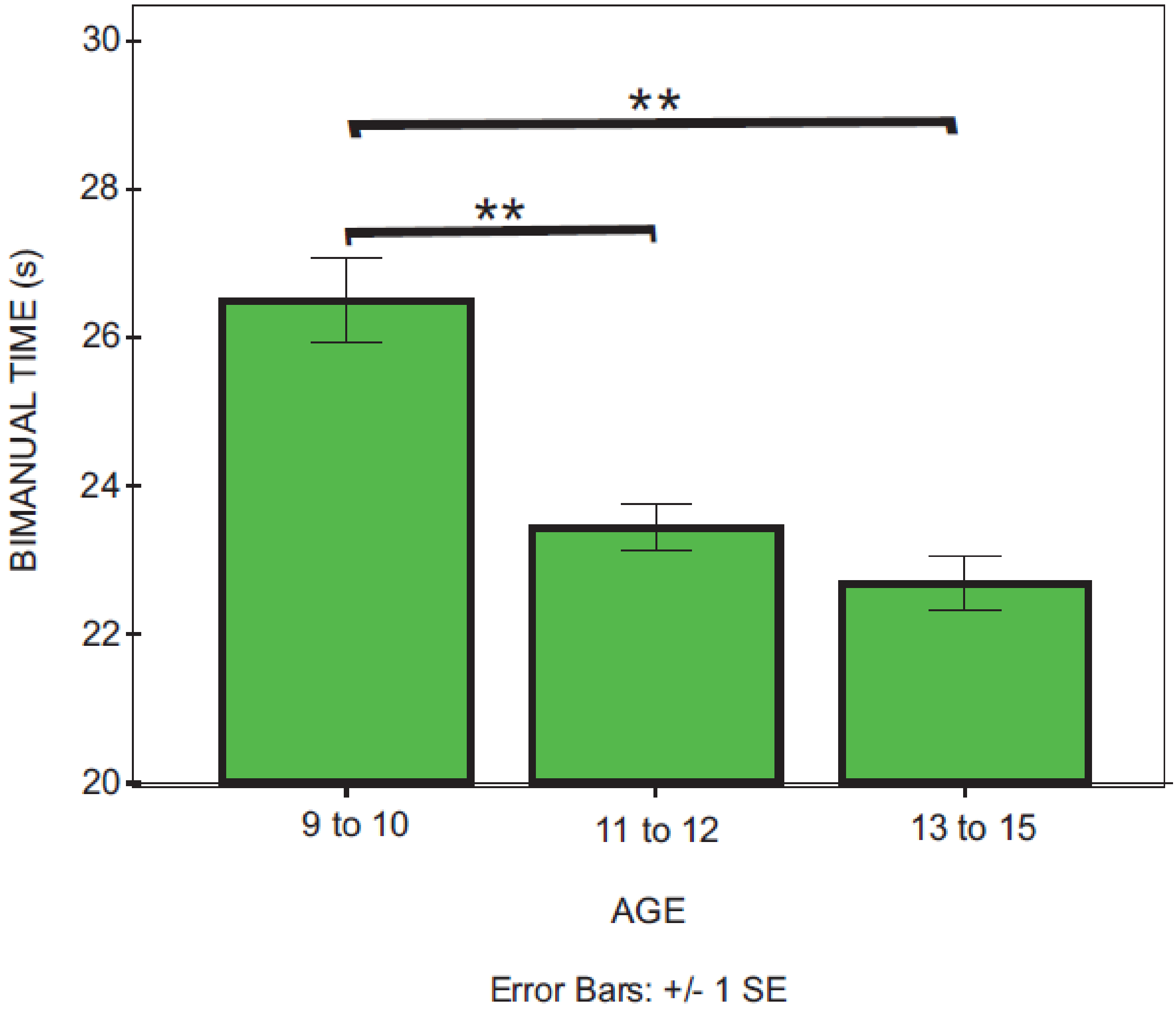

Figure 6. A comparison of group mean performance (measured in seconds) separated by age (9 to 10, 11 to 12 and 13 to 15) on the Precision bimanual task. Standard error bars represent +/- 1 standard deviation. Asterisks indicate (**) p<0.001.

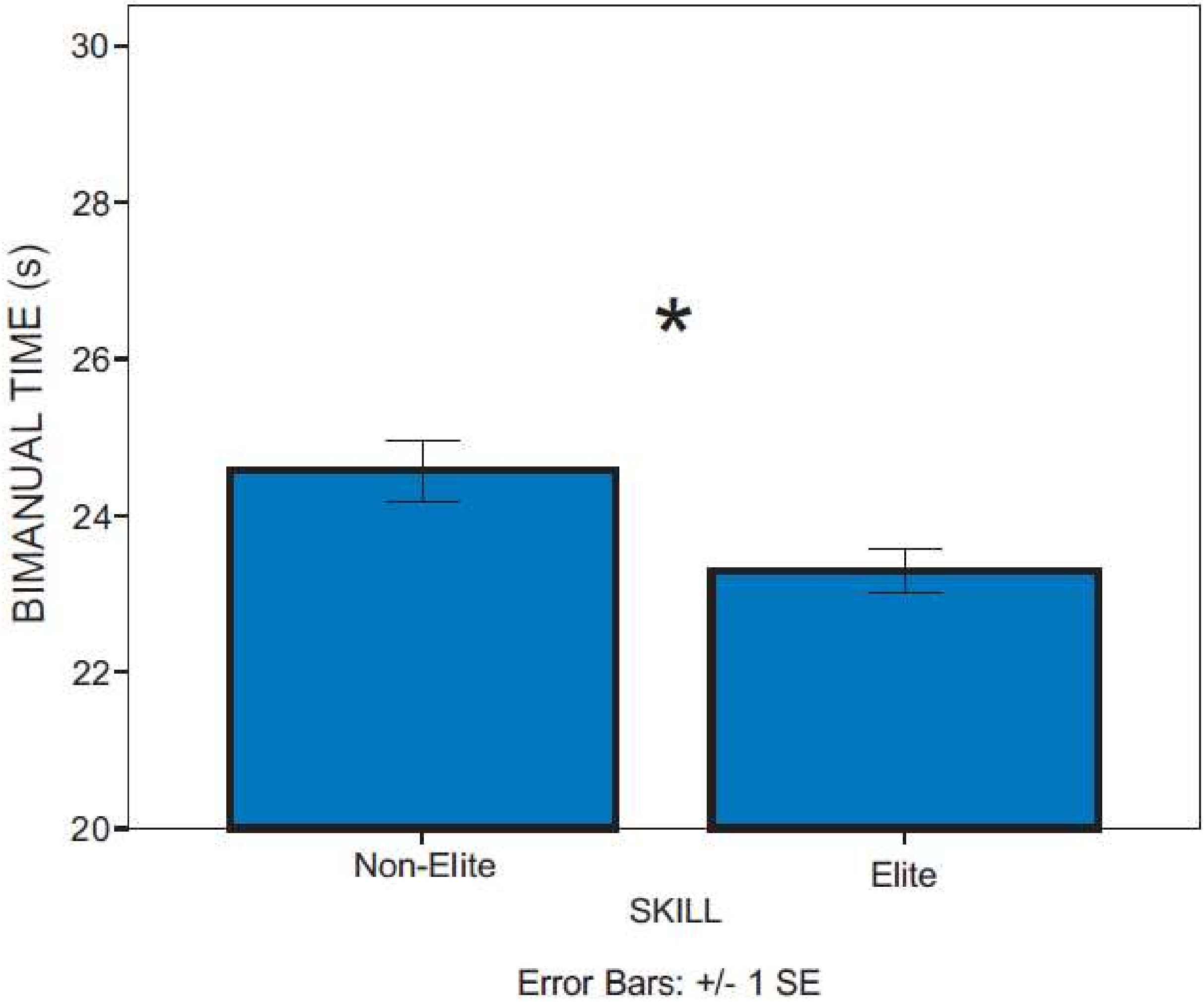

Figure 7. A comparison of group mean performance (measured in seconds) separated by Skill (Elite and Non-Elite) on the Precision bimanual task. Standard error bars represent +/- 1 standard deviation. Asterisks indicate (*) $p<0.05$.

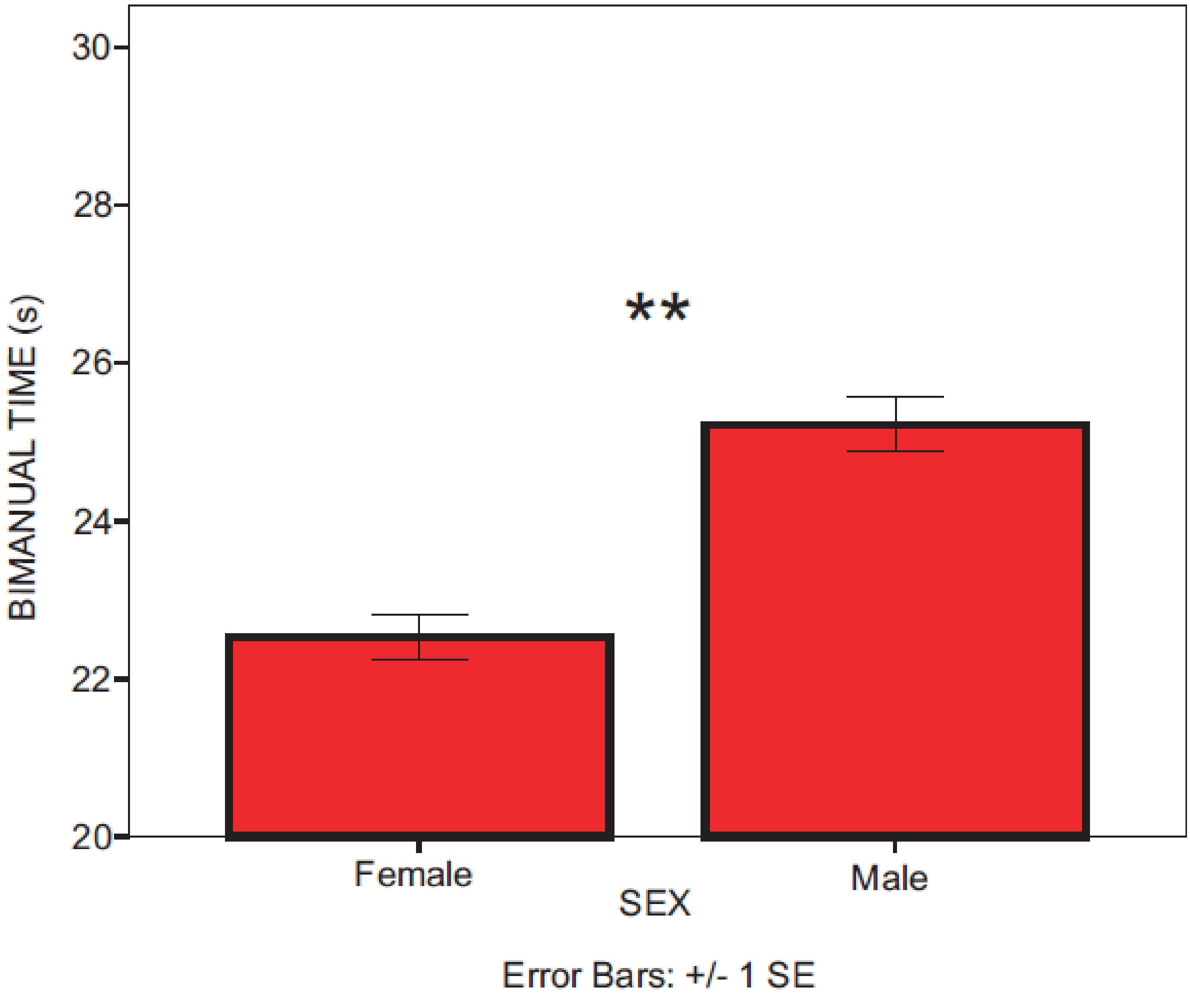

Figure 8. A comparison of group mean performance (measured in seconds) separated by Sex on the Precision bimanual task. Standard error bars represent +/- 1 standard deviation. Asterisks indicate (**) p<0.001.

Whole-Hand Bimanual Task

The time it takes to complete the Whole-Hand bimanual task (median = 16.54 seconds) is faster than the precision bimanual task (median = 23.36 seconds) because we have removed the precision aspect of the task, grasping washers and placing them on peg (n = 457, $x^2 = 162.83$, $p < 0.001$). As we observed for the Precision bimanual task, here we see a step-wise increase in bimanual performance, indicated by a decrease in time to complete task, as a function of age (Figure 9). Bonferroni Corrected post-hoc tests demonstrate that the fastest group is the 13 to 15 year olds, when compared to 9 to 10 year olds (n = 140, $x^2 = 41.35$, $p < 0.001$) and 11 to 12 year olds (n = 190, $x^2 = 21.30$, $p < 0.001$). Thus in contrast to what we saw with the precision bimanual task, there is not a plateau in the performance of the two older age groups (11 to 12 and 13 to 15). Further, in the Whole-Hand bimanual task we still retain our skill effect. That is, Elite-level athletes are able to perform this bimanual task faster than Non-elite-level athletes (n = 256, $x^2 = 8.73$, $p < 0.01$) (Figure 10). Lastly, we were able to support the argument that females perform better than males on our bimanual tasks. Even when we removed the fine motor skill component - the requirement to grasp and place a washer from one peg to another - the sex-related difference persists in the Whole-Hand bimanual task (n = 256, $x^2 = 4.40$, $p < 0.05$) (Figure 11).

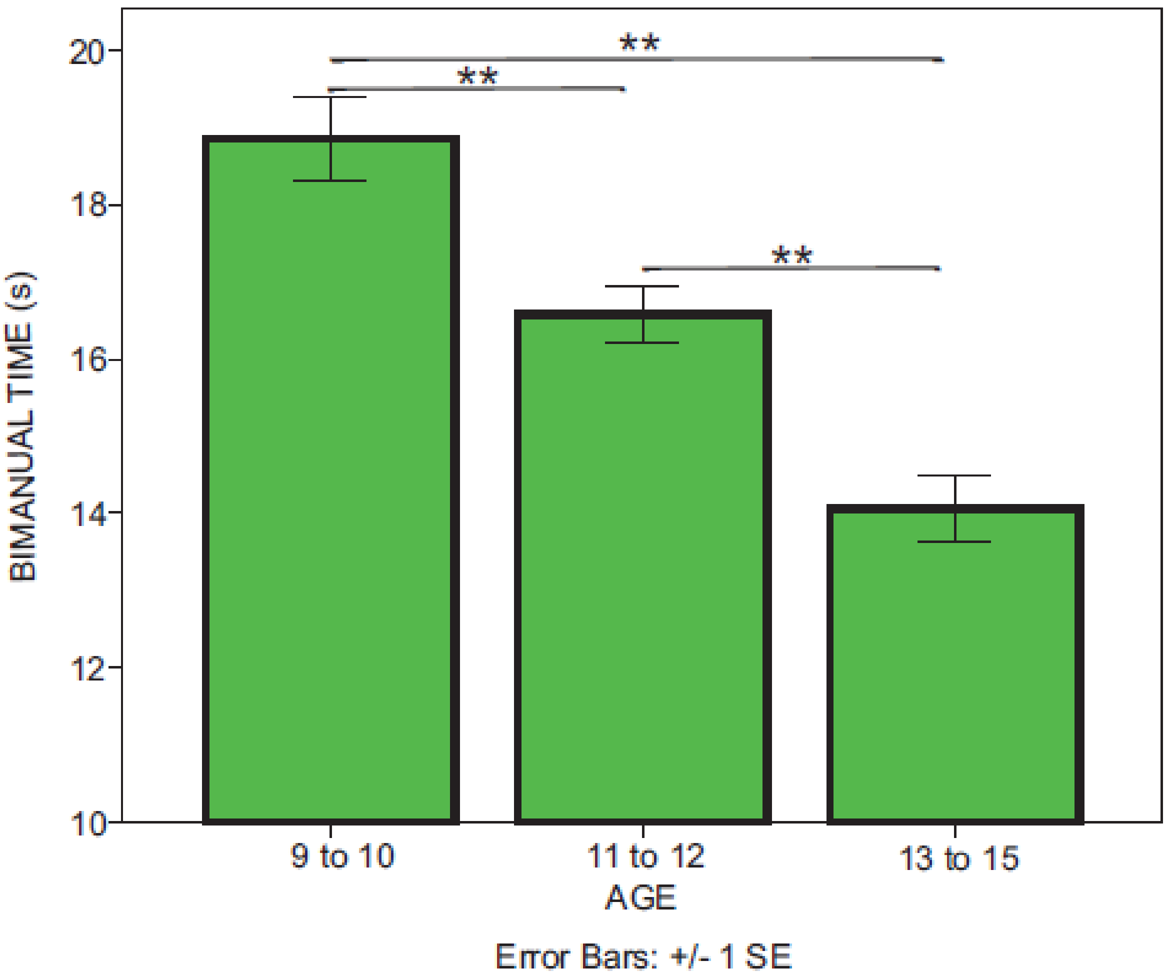

Figure 9. A comparison of group mean performance (measured in seconds) separated by age (9 to 10, 11 to 12, and 13 to 15) on the Whole-Hand bimanual task. Standard error bars represent +/- 1 standard deviation. Asterisks indicate (**) p<0.001.

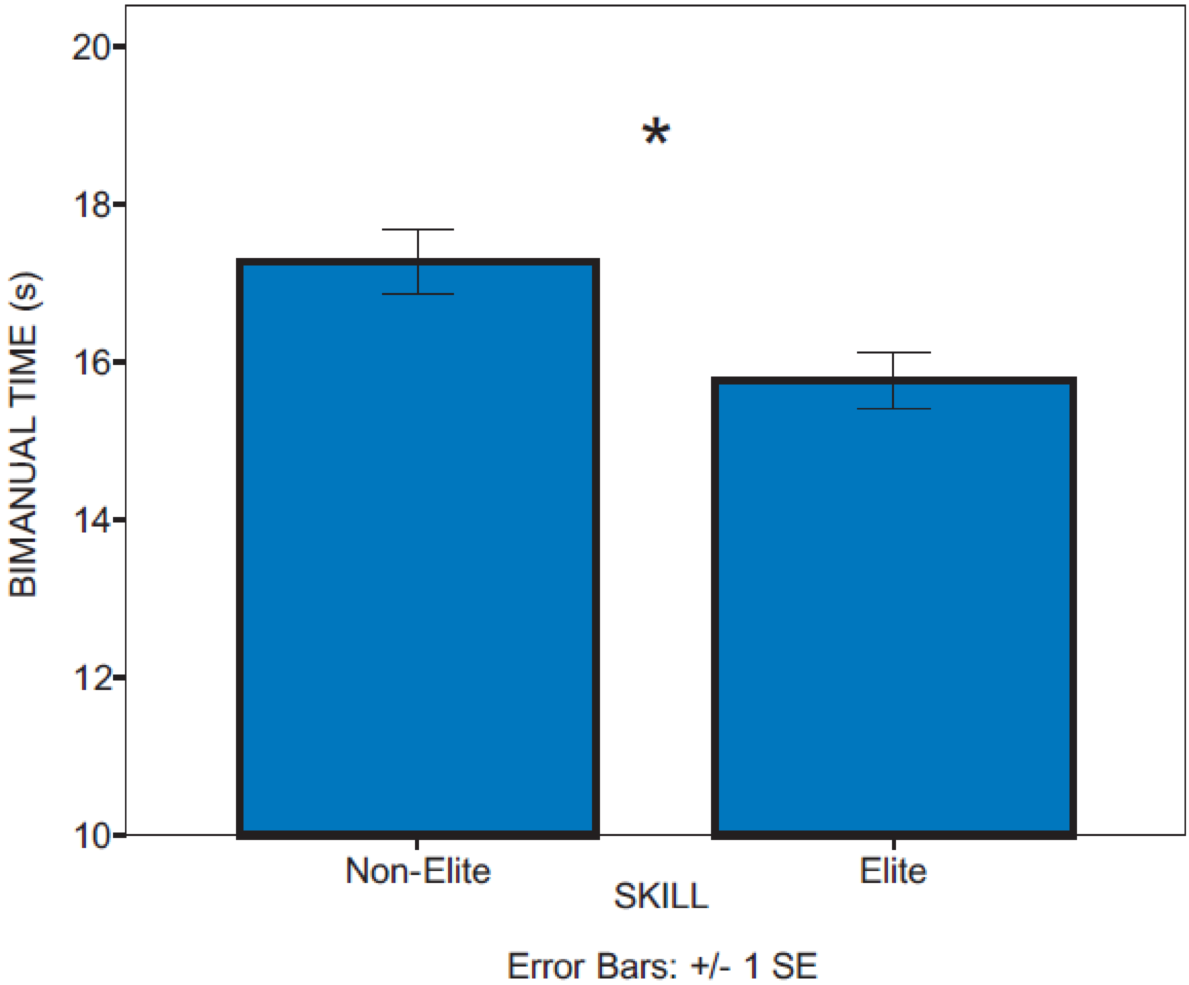

Figure 10. A comparison of group mean performance (measured in seconds) separated by Skill (Elite and Non-Elite) on the Whole-Hand bimanual task. Standard error bars represent +/- 1 standard deviation. Asterisks indicate (*) $p<0.01$.

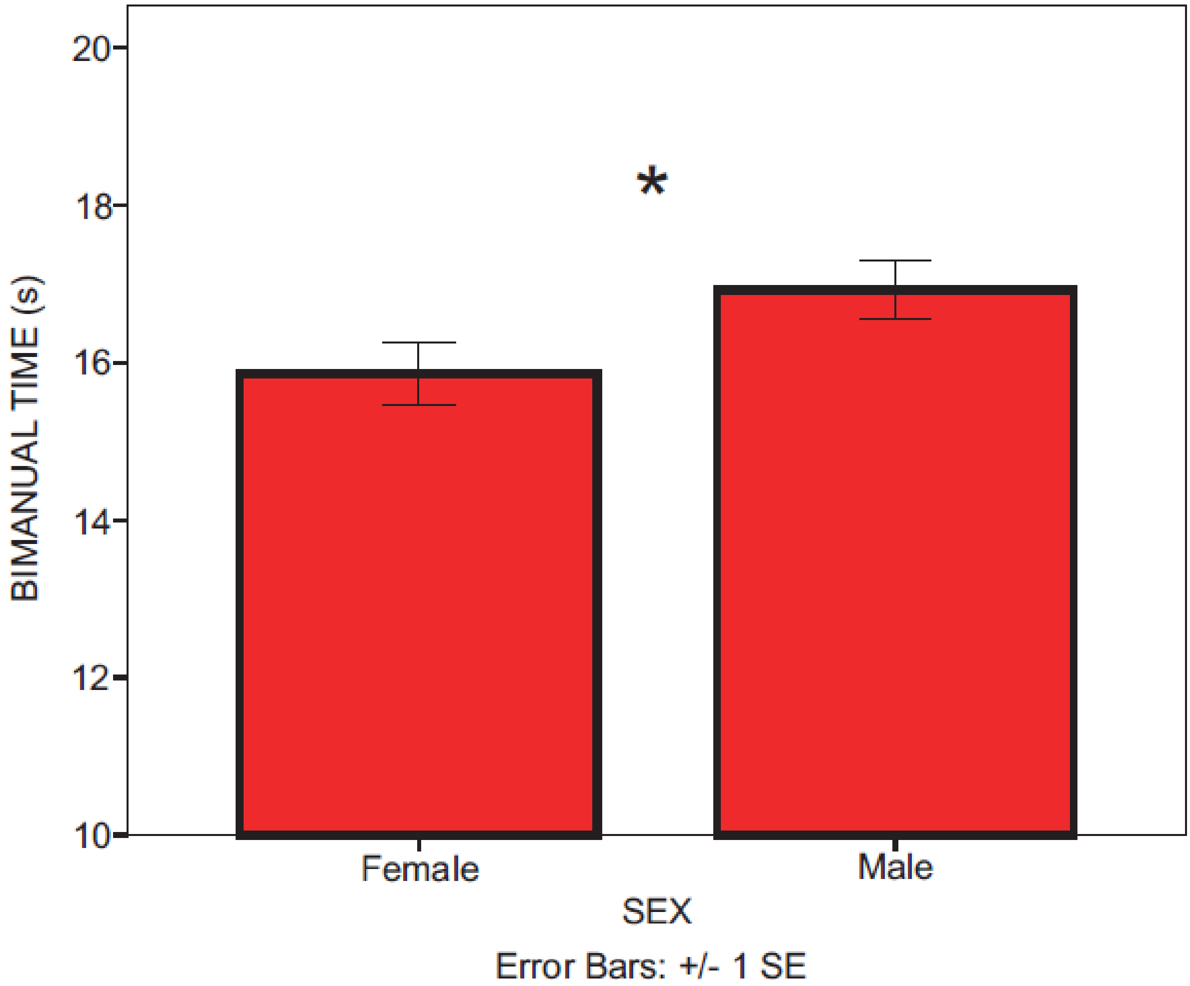

Figure 11. A comparison of group mean performance (measured in seconds) separated by Sex on the Whole-Hand bimanual task. Standard error bars represent +/- 1 standard deviation. Asterisks indicate (*) $p<0.05$.

Further analyses

Throughout our data collection we asked participants the age at which they first started to play their particular sports. This was done with the aim of continuing with the work done by Schlaug, et al. (1995). In that study the authors observed a change in the structure of the corpus callosum with musical training that commenced before the age of 7. In the current study, we did not observe a correlation between the age of practice onset and bimanual time, in either task. In addition we recorded the handedness of the players using a modified Edinburgh Handedness Inventory (Oldfield, 1971). The majority of athletes tested were right handed with only 12 left handers and 18 mix handers. Interestingly, there was a significant difference for the Precision bimanual task but not with the Whole-Hand bimanual task (Figure 12) as a function of handedness. With further investigation, using Bonferroni Corrected post-hoc tests, we found that mix handers performed the Precision bimanual task faster than right handed subjects ($n = 240$, $x^2 = 6.51$, $p < 0.05$). There were no significant differences when we compared right handed and left handed groups ($n = 234$, $x^2 = 0.276$, $p > 0.05$).

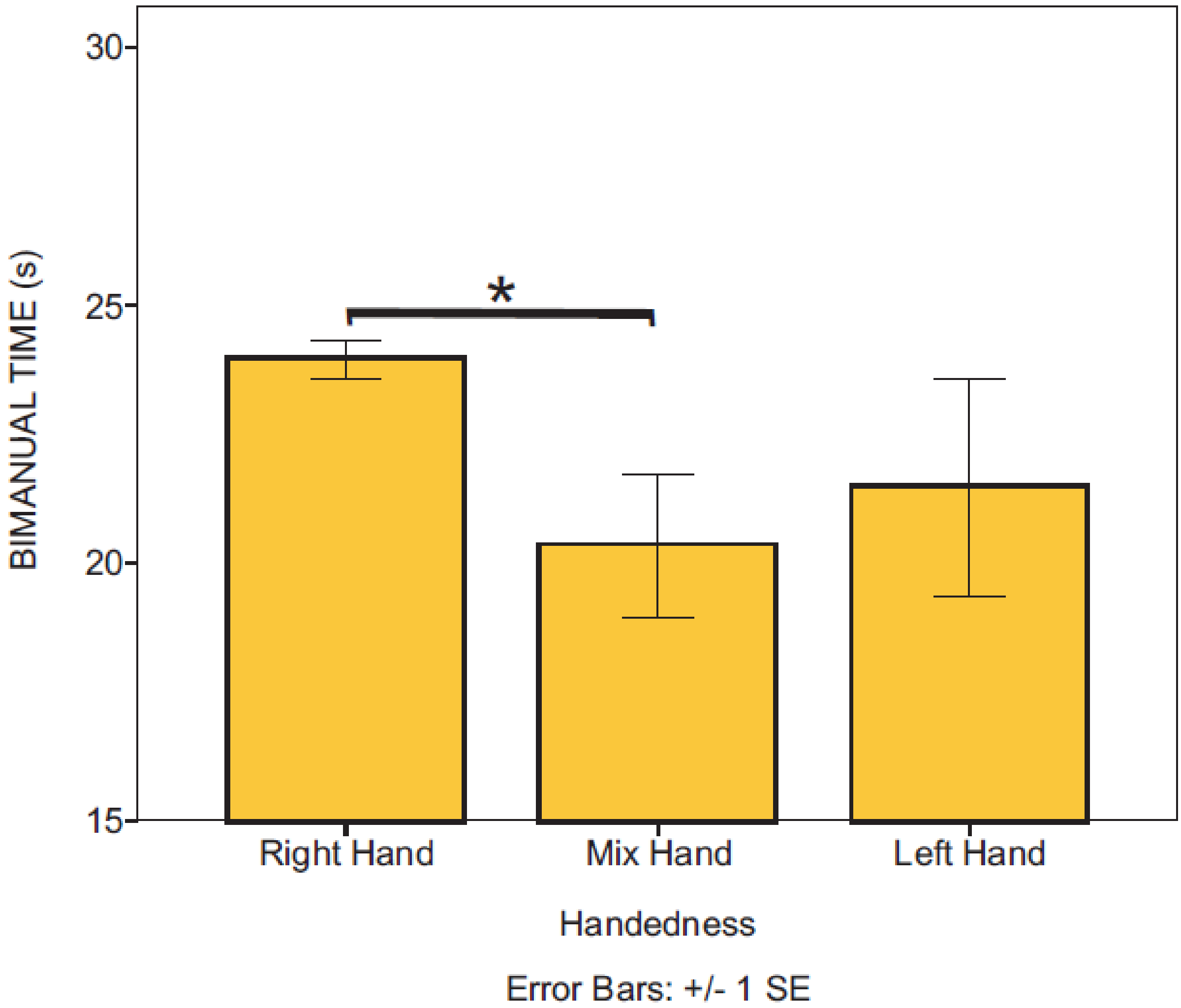

Figure 12. A comparison of group mean performance (measured in seconds) separated by Handedness on the Precision bimanual task. Standard error bars represent +/- 1 standard deviation. Asterisks indicate (*) $p<0.05$.

Discussion

This study represents the first time that bimanual coordination development has been systematically studied in a large group of children across a range of ages and athletic experience. From these data came three main findings, the first of which supported our initial hypothesis. First, we observed that females were significantly faster at performing the bimanual coordination tasks when compared to males. This finding was especially prominent in the Precision bimanual task which included a larger dexterity component relative to our other bimanual task. Second, we characterized the age-related development in reaction time performance in both bimanual tasks. Interestingly, there was a huge leap in terms of development in going from 9/10 to 11/12 years of age. For the whole-hand bimanual task there was further development past the ages of 11 and 12. Lastly, we found that elite-level athletes were able to complete both tasks at faster times relative to non-elite athletes across all age ranges and both sexes. Although not a main objective of this project, we also looked at how handedness influenced these children's performance. To this end we found that individuals that were classified as mix-handers completed the Precision bimanual task faster than those that were right-handed. However, there was no significant difference between left-handers and mix-handers. Also, there were no significant differences between the three handedness groups with the Whole-Hand bimanual task.

Age-Based differences and the influence of handedness on performance

Bimanual coordination relies heavily on the integrity of the CC, the main fibre bundle joining the cerebral hemispheres. For example, damage or removal of the CC results in the inability to perform previously learned bimanual tasks (Eliassen et al., 1999). Prior research shows that near the end of 10 years of age the anterior portion of the CC reaches a stable state in myelination (Thompson et al., 2000; Giedd et al., 1996). The posterior portion of the CC which joins left and right parietal regions, however, continues to develop further into the late teenaged years and into the early twenties (Thompson et al., 2000; Giedd et al., 1996). The anterior portion of the CC allows for interhemispheric communication between the left and right SMA regions in the frontal lobe, which is important for planning and performing bimanual movements (Obhi et al., 2002). Interestingly, researchers have noticed an increase in SMA activation when a task demanded the use of both hands in different motor actions (Obhi et al., 2002). However, until myelination in the posterior CC is fully developed inter-hemispheric communication between parietal areas is limited. An important cortical area for the control of reaching and coordination of limb movements is the superior parietal lobule (Debaere et al., 2003), part of the posterior parietal cortex (PPC). The PPC provides information of limb location that is important for motor programs such as visually guided reaches and is also active for during bimanual coordination tasks (Kermandi et al., 2000). Because in this study we used a novel task, our study participants likely needed to rely on the information provided from these parietal areas (Debaere et al., 2003). Presumably, the older subjects had greater myelination of the CC which likely resulted in a more efficient transfer of information from one hemisphere to the other. This more highly developed CC myelination might explain the significant decreases in task completion times we observed in older subjects.

Interestingly, when the study participants completed the Precision bimanual task there was only a significant increase in performance when comparing ages 9 and 10 to 11 and 12 years of age. There was no statistically significant further development with age. In contrast, looking at the Whole-Hand bimanual task performance we see a step increase in performance when going from ages 9 and 10 to 11 and 12 but also an increase from 11 and 12 to 13 and 15. We believe that the differences between the two tasks could be that the Precision bimanual task was more difficult for all groups, and thus our participants reached a plateau in performance. That is, a really difficult task might not give any one group a developmental advantage, whereas an easier task could allow us to see that something that is simple at 15 years of age but less so at 9 years of age. Creating a task that is challenging but not so hard that everyone performs equally poorly is something that takes a lot of trial and error. It would be interesting to see what the time to complete both tasks would look like if we extended the ages to 21 years of age. At 21 years of age the CC development would be nearing its completion, which could potentially be at peak performance because CC integrity decreases with age (Ota et al., 2006).

Our findings indicate that mix-handed participants were significantly faster with the Precision bimanual task than right-handers, across ages and experience levels. Since this result was not observed in the Whole-Hand bimanual task, we suggest that this enhanced performance is attributable to the additional manual dexterity component of the precision task (i.e. manipulating washers and pegs). Thus, the ability to manipulate small objects with one hand while manipulating a large object with the other appears to benefit from a brain that does not have pure unimanual dominance. The underlying neural structures that are related to handedness, and their contribution to eye-hand coordination, remain open questions for future study.

With respect to motor behaviour, researchers have found that there are a greater amount of mix-handers within 8 to 15 year-olds (Brito & Santos-Morales, 1999) relative to older age groups. After this time period we start to see a distribution of handedness that is similar to adults (Brito & Santos-Morales, 1999). For the current research, the Perdue pegboard test (PPT) was kept in mind when designing the bimanual tasks. We aimed to have a task that would force the individuals to use both their hands in a coordinated manner. To add to the level of difficulty we had participants alternate their hands. Research that has been done with the PPT has shown that left-handers have an advantage over right-handers when performing the assembly portion of the test (Judge & Stirling, 2003). Judge et al. (2003) believes this is attributed to left-handers having a greater ability to use their non-preferred hand (right hand). The assembly task requires the participant to grab a peg, place it in the board, then with the other hand to grab and place the washer onto the peg, this continues with alternating hands. Placing the washer onto the peg requires great control and coordination. Left-handers seem to be able to use both hands equally well during this portion of the PPT and do not lose time when having to grab and place the washer with their non-preferred hand. Unfortunately, this study only looked at right- or left-handers and did not classify participants in a mix-hander group. Based on our findings, one might expect that mix-handers would have an even greater advantage with the PPT than left-handers. With our task, it seems that having a non-preferred hand that is less coordinated increases the time and effort to perform our tasks. Prior literature suggests that around the ages of 5 we have a lower degree of left-right hand difference in coordination (Roeder et al., 2008). However this gradually changes as we are introduced to newer tasks and start to prefer the dominate hand. At this point we have increased the ability of one hand and the other has been left behind. The last developmental change related to handedness is an increasing ability of the non-preferred hand which results in a decreased left-right hand difference and therefore aids in better bimanual coordination. Therefore the fact that the slowest group was ages 9 and 10, in both of our tasks, is likely attributable to both the lack of coordination in their non-preferred hand and the incomplete myelination of the CC, discussed above. It is also worth mentioning that we did not see that left-handers perform faster than right-handers, but there was a statistical trend for this behaviour. Perhaps if we had equal group sizes this result would have resembled previous research.

Experience-Based Differences

There is evidence of structural changes in the brain when children commence musical training before the age of 7 years old (Schlaug et al., 1995). In this study it was observed that the anterior half of the CC was significantly larger in musicians with early commencement of training when compared to those that started training after 7 years of age (Schlaug et al., 1995). Although, the results were not included in this thesis, we asked all participants at what age they started playing their sport. We predicted a positive correlation when looking at the relationship between the age the child started training and their bimanual total time. However, we did not find a statistically significant correlation between the age they started to play their sport and their bimanual task times.

There is empirical evidence that when learning a new task, more specifically a bimanual task, there is an increase in neural activation over a broad range of brain regions. Once a large amount of practice is attained, the level of activation decreases and becomes more lateralized and localized. One question that arises is whether there are individuals that are better (faster) at learning a new task, and can this be related to underlying neurophysiology? A study conducted by Fattapposta et al. (1996) looked at the amount of brain activation when giving two groups a novel task. The trained group that they used were selected from the Italian Modern Pentathlon Federation (trained for longer than 10 years). Modern pentathlon comprises five Olympic events: fencing, swimming, show jump, pistol shooting and a cross-country run. Using EEG they monitored the level of activation in target brain areas. After only one block of trials the trained group were performing better, which was measured by number of correct performances. After the completion of four blocks they had noticed that the trained group performed better overall and also that the last block for the untrained group looked like the first block of the trained group. This indicates that trained individuals have an advantage when it is pertains to learning a new task. Not to say that those of us who are not elite athletes are not capable of learning to the same degree, this was not the aim of the study, but that they required a greater amount of practice. In addition they found that the trained group had a lower amount of activation in the premotor cortex just before initiating the task, when compared to the untrained group. Also, they had a slight decrease in activation with high level performance. Conversely, the untrained group had a positive correlation, where an increase in premotor activation resulted in better performance. They suspect that these effects were specifically localized in the SMA. Regardless of the complexity of the task, trained individuals had lower levels of premotor activation, indicating perhaps greater neural efficiency. Although we did not see a correlation with the age at which the child started training in their principal sport, we did see that elite level athletes performed better on our bimanual tasks. Perhaps this is due to the increased ability to learn new motor tasks. Such an ability may be related to naturally more efficient brain networks activated when learning a new motor skill. Again, while the present study was behavioural in nature, these data point to future neurophysiology studies that would get at the basis to elite performance. In the present case, an examination of brain connectivity between premotor cortex and sensorimotor control regions such as parietal cortex and motor hand regions (using neuroanatomical imaging techniques such as diffusion tensor imaging) in elite- versus non-elite level athletes learning a bimanual coordination task might prove insightful.

Sex-Based Differences in Bimanual Coordination

Our present study supported our initial hypothesis in that we showed a significant sex effect in both bimanual tasks, with females performing the task faster than males. We speculate that this may be due to structural differences within the CC. Myelination of the CC develops in a rostral to caudal direction in both boys and girls; however, myelination seems to occur at an earlier age in girls (Allen et al., 1991; Thompson et al., 2000). Such callosal myelination may be a reason behind our observation that performance of females is improved when compared to age-matched males simply because at any given age females tend to have greater interhemispheric connectivity.

Other studies have shown sex-based differences in visuomotor behaviour. For example, a simple bimanual and unimanual tapping task was tested in children ages 5 to 7 (Denckla, 1973). They noticed that the speed of tapping increased with age. Interestingly, they also found a sex effect showing that in each age group females were faster, suggesting an earlier development of coordination. After performing an alternating tapping task there was a small percentage of boys aged 5 and 6 that were unable to complete the task, which was not the case with girls in any age group. The fact that 5 and 6 year old boys were not able to alternate tapping indicates a development delay. The task of alternating hands requires the use of both hemispheres, inability to perform the task might be a result of poor connectivity. The advanced development of coordination in girls for this task could be a result of earlier CC myelination. In addition to being further along in myelination there is direct evidence of a greater amount of inter-hemispheric connectivity in females. Regardless of training, females tend to have a more bulbous splenium, suggesting the presence of more connections (Allen et al., 1991). Other research has shown that males have greater within hemisphere connectivity which starts at an early age (Ingalhalikar et al., 2013). In contrast, females have greater interhemispheric connectivity in the frontal area relative to males in early adolescence and this greater inter-hemispheric connectivity in females continues to develop and increase into adulthood (Ingalhalikar et al., 2013). This may be beneficial for increased efficiency of communication across hemispheres, which is important when performing bimanual tasks. This is especially true when the task used is novel to the participants. A novel task requires greater bilateral activation, something that females appear to be at a structural advantage.

It is well known that there are sex differences in the performance of some motor skills. In general, boys have better ability in ball skills and girls are often better at manual dexterity tasks (Junaid & Fellowes, 2006). Boys also tend to perform better in tasks that require a great amount of force production (Thomas & French, 1985). This sex difference increases after puberty because of the relatively larger increase in muscle mass in males (Flatters et al., 2014). It is important to note, however, that there are also other opinions that state this increased performance in ball skills could be by because of the amount of positive reinforcement that boys received (Barnett et al., 2010). Thus some of these performance findings may be more sociocultural in nature than strictly biological.

Taking together, the sex differences that we observed in our study is likely attributed to a combination of the earlier age of development of CC myelination in females, the larger CC and greater number of inter-hemispheric connections in females, and lastly the increased ability that females tend to have when performing dexterous tasks. Based on the literature we predicted that females would have an advantage in the Precision bimanual task. Interestingly, although the Whole-Hand bimanual task lacked the fine motor skill component of the precision bimanual task, we still saw a sex effect. This finding suggests that our observation of faster bimanual task times in girls cannot be entirely attributed to better fine motor skills. Even so, it is important to point out that the significance level of the sex-based differences was lower in the Whole-Hand bimanual task compared to the precision task. The increase in effect size between the Precision bimanual task and the Whole-Hand bimanual task (significance values of $p<0.001$ and $p<0.05$, respectively) suggests that dexterity was a factor for this analysis.

Limitations

One of the issues that could have affected out results is the fact that we had several testers. This was because we would only have teams for a short period of time and needed to collect data as quickly as possible. Testers were thoroughly trained on how to teach the tasks and were given a guideline of how much practice subjects could have before performing the task. Regardless we did not have a script that the testers had to follow which could have created a discrepancy in the amount of instruction that one participant received compared to another. Also, at times participants would start the Precision bimanual task and drop the washer from the testing surface and when this occurred testing was stopped and restarted which inadvertently provided some participants with more practice than others. Also, there were several testing locations because we went to where the practices were held (soccer fields, football fields, and hockey arenas) adding unavoidable inconsistency to the data collection environment and levels of potential distractions. At times data collections occurred in a hockey arena where noises of other teammates and parents were unavoidable. This could have distracted participants but in other cases the pressure of nearby teammates could have motivated them to get a faster time. In either case we tried to eliminate distractions but the tests sites were not in a controlled environment. In other bimanual studies there is an inclusion of a unimanual task that is performed with each hand to compare the performance of unimanual and bimanual coordination. The benefit of having this information is to ensure that there are no individual issues that might have resulted in a slower bimanual time. This is meaningful because we know that bimanual time could decrease, meaning better performance, due to an increased control of the non-preferred hand. We did not include a unimanual task because of the time constraints of our data collection.

Lastly, the classification of elite versus non-elite is difficult to define. In this study we separated the two based on their level of competition. Non-elite participants played in house league and elite participants played in select, REP or AA/AAA. These classification criteria were chosen because higher levels require a lot more time in their sport then lower levels. Higher level players also receive more one-on-one attention due to the greater amount of coaches and other support. These criteria however, cannot accommodate for participants that play in house league because they cannot afford or do not have the time that higher levels demand. In addition, other than age at which participants commenced training we did not take any other information on prior history. We are aware that earlier exposure to various tasks can influence result but this could only be accurately addressed by conducting a twin study, which was outside the scope of this study.

Conclusions - Implications and Future Studies

The results presented here are important for our fundamental understanding of motor development. We now understand that there are sex differences not only in motor output but also in how the brain behaves when men and women are performing the same task (Gorbet & Sergio, 2007; Gorbet & Staines, 2011). This is also true when looking at functional MRI data of how experience can change the brain networks that are used (Granek, Gorbet & Sergio, 2010). By increasing the research within these age groups we can then determine what is classified as normal development. This type of information is important to clinicians who determine if a child is developing properly. Some conditions that are associated with delayed motor skill development are fetal alcohol syndrome, premature births, attention deficit hyperactive disorder, autism, schizophrenia, and traumatic brain injury (Bellgrove et al., 2001; Caeyenberghs et al., 2011). Conversely, individuals in physical education and coaches could benefit from this information as well. This information will give us a better understanding of potential limits and reasonable target expectations within a given age group. These results can also extend to product development. For example, if we know that bimanual coordination is poor in 10 year olds then perhaps the games that are developed need to account for this potential limitation. Lastly, we can use this information to help rehabilitation clinicians. A prime example is people that have undergone cerebrovascular accident. With continued understanding of sex differences in motor control we could start to cater to each sex. If, in general, females tend to have more interhemispheric communication than males then perhaps they could benefit more from bimanual training rehabilitation approaches. There are already studies showing improvement in hand force control with the addition of bimanual training (Kang & Cauraugh, 2014).

To get a better understanding of what occurs during the critical ages of 9 to 15 and to gain further insight into sex-related effects, we would like to adapt our tasks to examine the removal of the alternation of hands. This would allow us to see the effect of using the preferred hand for the more difficult aspect of the Precision task (grasping the washer) compared to the non-preferred hand. This way we can get a closer look at the true effects of handedness and begin to disentangle whether some of the increases in bimanual coordination with age that we found here were a result of increasing the abilities of the non-preferred hand.

We noticed that some participants tried to develop a strategy for the Precision bimanual task. There instruction of the Precision bimanual task was to grab a washer then place it on the peg. In order to place the washer on the peg the other hand must lift it up. This was then repeated but the role of each hand was alternated. Interestingly, some participants assigned each hand a task, for example one hand would grab the washer and place it on the peg and then the other hand had to open the hinge. Therefore, by doing the task in this manner they tried to assign the more dexterous task to their dominant hand. This strategy could have been to try to decrease the complexity of the task. Other research suggests that when performing a bimanual task people will often assign the more complicated or lead to their dominate hand (Amazeen et al., 2005). Performing this type of error or any error in general was not recorded. Perhaps if we recorded errors there might have been a trend for individuals that wanted to assign the more complicated task, grasping the washer with their dominate hand, there may have been a correlation with handedness and this desire to simplify the task. .

In conclusion, our research increases our understanding of the normal development of bimanual coordination in children aged 9 to 15. In addition our data show that females and elite athletes tend to be better able to coordinate their hands in a bimanual task when compared to males and non-elite athletes. Future research that aims to look at the development of motor skills and control should also look at sex and experience effects.

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