Bimanual Performance in Unpredictable Virtual Environments

A Lifespan Study

Andrea H Mason, Drew N Rutherford, Patrick J Grabowski
Department of Kinesiology
University of Wisconsin - Madison
Madison, USA
amason@education.wisc.edu, anrutherford@wisc.edu, pgrabowski@wisc.edu

***Abstract*—Interaction and interface design for the young and the elderly has become an important research topic. The purpose of the research described here is to characterize motor performance in virtual environments across the lifespan. Participants between the ages of 7 and 90 years simultaneously reached to pick up two objects with their right and left hands in a desktop virtual environment. On random trials, objects were unexpectedly moved to new locations. Results indicated that older adults used different movement strategies in the virtual environment when compared to results from natural environment experiments. Further, children and older adults responded to perturbation conditions with different movement time and hand coupling strategies than young and middle-aged adults. These results suggest that age and task-specific design is necessary to ensure general access and optimal performance in virtual environments.**

Keywords- virtual environment; aging; motor control; bimanual reach to grasp

I. Introduction

A. *HCI and Age*

With the expansion of the role of computers in schools, the workplace, and homes, the population of users who make regular use of computing technology has grown exponentially. Unfortunately, Human-Computer Interaction (HCI) research has not reflected this demographic reality. Results of the 2010 US Census show that 17.5% of the US population is between the ages of 5 and 18 and a further 40% of the population is above the age of 45 [1]. It has also been reported that Europe is experiencing an aging population, with projections of 35% of the population being above the age of 65 by 2025 [2]. Still most HCI research is focused on younger people, often university or college students [3]. Rather than representing the true population of computer users, most experimental HCI research is biased heavily towards the cognitive and motor abilities of young adults. Where age-specific research has been conducted, the majority relates to the design of standard computer interface systems for various age groups. In particular, research has focused on ways to improve cognitive performance through specific training or tutorial methods [e.g. 4, 5], or on the age-appropriate design of input devices [e.g. 6, 7, 8].

While a modest corpus of knowledge is available for the design of standard computer interface systems for a variety of age groups, much less is known about how age influences performance within immersive three-dimensional virtual environments (VEs) [9, 10, 11]. Immersive VEs are becoming more prominent as the costs of the relevant tracking and display technologies decrease. VEs are commonly used in design and prototyping, data visualization, medical training, architecture, and entertainment. Further, recent research has focused on the utility of VEs for rehabilitation of motor impairments such as stroke in the elderly and attention deficit hyperactivity disorder (ADHD), developmental coordination disorder and cerebral palsy in the young [12, 13]. However, because there is a paucity of information on how healthy children and older adults interact in VEs, it is likely that the success of these systems will struggle. Specifically, it is nearly impossible to extrapolate design characteristics from healthy young adults to special-needs children and older adults. Results of the few studies conducted on performance across age-groups within virtual environments indicate relevant disparities in reactions to environmental immersion, usage of various input devices, size estimation ability, and navigational skills [9, 10, 11]. According to Allen et al. [9], “these results highlight the importance of considering age differences when designing for the population at large.”

The purpose of the research described here is to characterize motor performance in virtual environments across the lifespan. To do this we asked participants ranging in age from 7 to 90 years to perform a foundational skill (bimanual reach to grasp) within a table-top virtual environment. In the following sections, we describe the importance of the skill we chose to study.

B. *Bimanual Reach to Grasp Skills*

The performance of many everyday activities requires the completion of asymmetric but coordinated movements with our two hands. For example, touch typing, tying our shoelaces, and even reaching for a mug with one hand and a coffee pot with the other require the performance of two separate but coordinated movements. Many asymmetric bimanual tasks such as the ones described above can be performed quite effortlessly in natural environments. This seamless control is possible because we use feedforward sensory information (vision and proprioception) to pre-plan our movements and feedback sensory information for on-line corrections during movement execution.

Recently, bimanual tasks have been targeted as important skills to (re)train in rehabilitation protocols employing natural environments and virtual reality [14]. In rehabilitation training after stroke, these types of tasks are important for functional recovery because they require the areas of the brain most commonly afflicted by stroke to work with areas usually left undamaged, thereby maximizing the potential for positive neuroplastic changes [15].

While the study of bimanual movements has received some attention in natural environments, very little is known regarding the performance of these types of movements in virtual environments [16]. Further, no studies have looked at how the control of bimanual skills changes as a result of age in VEs. In order to successfully implement rehabilitation and training protocols that make use of these types of tasks it is imperative that we first obtain a baseline understanding of how neurologically "normal" people across the lifespan perform bimanual skills in VEs and how they use sensory information for the performance of these skills.

In natural environments, results from bimanual movement studies have indicated that when the two limbs are used to accomplish both symmetric and asymmetric task goals, coupling between the limbs for certain parameters occurs in the temporal domain [17, 18]. In particular, movement onset, duration, and end times tend to be similar for the two hands when subjects aim toward or reach to grasp targets of different sizes or at different locations [17, 18]. However, timing differences between the hands have been shown, and results indicate that these differences are associated with insufficient visual feedback for movement control [19]. In the current study we investigated whether the same patterns of results are seen in virtual environments and whether these patterns change with age. We employed a target perturbation to specifically investigate how sensory (visual) information is used on-line by participants of various ages to modify their movements. These paradigms are discussed in more detail in the following section.

C. *Unpredictable Environments: Perturbation Paradigms*

An experimental paradigm that has been successfully used to investigate the role of on-line visual information for the performance of goal directed tasks uses target perturbation to study adjustments to ongoing movements. The use of this type of paradigm allows us to discern how long it takes the nervous system to adapt to an unexpected visual change as well as the efficiency of the adaptation.

In a target perturbation paradigm, the participant is unexpectedly presented with the requirement to alter their original movement plan either prior to or after movement onset. An example of a typical perturbation paradigm is as follows. A visual stimulus is presented to the participant prior to movement initiation and the participant generates a movement plan appropriate to the acquisition of the target at this initial location. Shortly prior to or after movement onset the stimulus is suddenly replaced by a second stimulus presented at an alternative location. The participant is thus required to reorganize their movement to successfully grasp the target at its new position. Results of studies using perturbation paradigms in both natural [20] and virtual environments [16] have indicated increased movement times to displaced targets and double velocity peaks in kinematic recordings.

Studying the performance of bimanual perturbation tasks in a VE can provide us with important information about how participants make use of visual information during the execution of a skill. This is particularly important given that the use of sensory information changes across the lifespan [21,22] and all the visual information presented to users of VEs must be synthetically created. By comparing results in the VE to studies performed in the "real" world we can determine whether performance is similar within these two environments.

II. METHOD

A. *Participants*

Fifty-one participants were divided into four age categories: Children (7-12 years, n=13), Young adults (18-30 years, n=12), Middle age adults (40-50 years, n=12) and Older adults (60+ years, n=12). Due to problems with data collection final data analysis was conducted on 12 participants in the "Children" group and 11 participants in the "Older adult" group. Decades of motor control research has indicated that a sample size of 10-12 participants provides sufficient statistical power in this type of reach to grasp study. All participants were self-reported right-handers and had normal or corrected-to-normal vision. All participants provided informed consent before taking part in the experiment. The protocol was approved by the University of Wisconsin-Madison Social and Behavioral Science Institutional Review Board.

B. *Experimental Apparatus*

This experiment was conducted in the Wisconsin Virtual Environment (WiscVE) at the University of Wisconsin-Madison. In this environment, subjects see three-dimensional graphical representations of target objects but interact with physical objects. As shown in Fig. 1, graphic images of two target cubes were displayed on a downward facing computer monitor. A half-silvered mirror was placed parallel to the computer screen, midway between the screen and the table surface. The graphic image of the cubes was reflected in the mirror and appeared to the participant to be located in the workspace on the table surface. Three light

Figure 1: Experimental apparatus

emitting diodes (LEDs) were positioned on the top surface of two wooden target cubes (38 mm). A VisualEyez 3000 motion capture system (Phoenix Technologies, Inc., Burnaby) tracked the three-dimensional position of the LEDs on the physical target cubes. This data was used with an 8–10 ms lag (which was not discernible to subjects), to generate the superimposed graphical representations of the cubes. A shield was placed below the mirror to prevent subjects from seeing the real environment or their hands as they performed the reach-to-grasp task.

Participants wore CrystalEYES™ goggles to obtain a stereoscopic view of the graphic images being projected onto the mirror. Three LEDs were fixed to the goggles and were used to provide the subject with a head-coupled view of the virtual environment on the work surface. Thus, when the subject moved his/her head, the displayed scene was adjusted appropriately for the magnitude and direction of head movement. LEDs were also positioned on the subject's right and left thumbs, index fingers and wrists. Data from all LEDs was collected at a sampling rate of 120 Hz and was stored for data analysis purposes.

C. Design and Procedure

Each trial began with the illumination of two blue circular start positions (radius 5 mm) located 12.5 cm to the left and right of the participants' midline. The participants moved their hands from the periphery of the workspace to place their index fingers and thumbs over the start positions, which were haptically indicated by small metal hex nuts. When the participants' hands were correctly positioned, the start positions turned yellow. Once both of the participants' hands remained stationary at the start positions for 1 s, the two graphic target cubes appeared at a location 20 cm from the start position. The task was to reach forward with the right and left hands to grasp and lift the two target cubes. Grasps were made with a precision grip and participants were asked to move at a comfortable pace once the target cubes appeared.

Participants experienced trials in four experimental conditions. In the control condition both targets remained at their initial location throughout the trial (left target no jump/right target no jump; NN). In the three perturbation conditions one or both targets were displaced 9 cm toward the participant at movement onset (defined as a displacement of 5 mm of the thumb LED). The perturbation conditions consisted of: 1) left target jump/right target no jump (JN), 2) left target no jump/right target jump (NJ), 3) left target jump, right target jump (JJ).

Participants performed a total of 100 trials. The first 10 trials were always control trials (NN). This allowed participants to become comfortable with the task and also gave us the opportunity to analyze a set of "control" trials where participants had no expectation of a perturbation. The remaining 60 control and 30 perturbation trials, 10 in each condition, were presented in a random order.

D. Data Analysis

Position data from the block LED as well as LEDs on the wrists of both hands were analyzed for specific temporal kinematic measures. Start of movement was defined as the point where wrist velocity increased above a threshold of 5 mm/s and continued increasing to a peak. End of movement was defined as the point where block lift velocity increased above 5 mm/s and continued increasing to a peak. Based on these two temporal measures we calculated Movement Time (MT) for both hands. We also quantified temporal coupling of the two hands by determining whether the hands started and ended movement at similar times. To do this we calculated the Absolute Start Offset (ASO: Start Left Hand – Start Right Hand) and Absolute End Offset (AEO: End Left Hand – End Right Hand).

Data were statistically analyzed in two ways. First, to quantify control performance in the first 10 trials, we conducted a 4 Group (Children, Young Adult, Middle Adult, Older Adult) X 2 Hand (left, right) repeated measures ANOVA on MT. To quantify bimanual coupling during the control trials a 4 Group (Children, Young Adult, Middle Adult, Older Adult) repeated measures ANOVA was performed on ASO and AEO. To quantify performance during the perturbation trials we conducted separate 4 Group (Children, Young Adult, Middle Adult, Older Adult) X 4 Condition (JJ, NJ, JN, NN) repeated measures ANOVAs for each hand and dependent measure. Post-Hoc analysis on significant main effects was done using the Fisher LSD method. When significant interactions occurred, these were further explored using simple main effects with Condition as the factor. An a priori alpha level was set at $p < 0.05$.

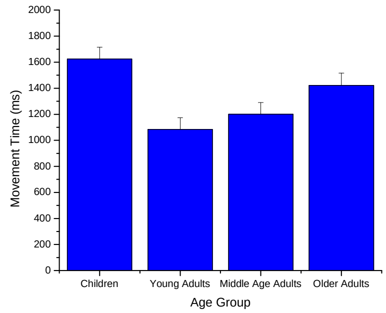

Figure 2. Main effect of Group on movement time in the control condition.

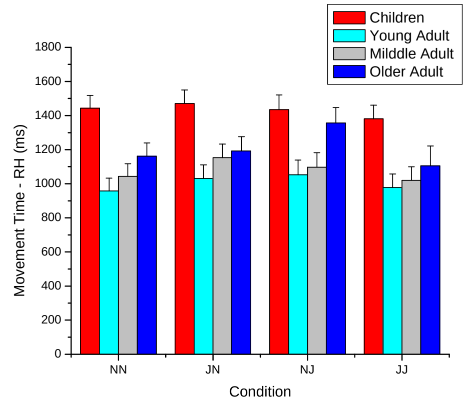

Figure 4. Group X Condition interaction for MT of the right hand.

III. RESULTS

A. *Initial Performance: Control Trials*

The control trials allow us to determine how bimanual performance changes as a function of age within virtual environments and whether patterns of performance in VEs replicate those seen in natural environments.

A main effect of Group was found for movement time ($F_{3,43}$ = 7.053, p=0.001). Results indicated that the fastest movement times were found in the young and middle aged adults. Children were significantly slower than the young and middle aged adults, whereas older adults were only significantly slower than the young adults (Fig. 2).

When looking at coupling between the left and right hands, main effects of Group were found for ASO ($F_{3,43}$ = 14.03, p<0.001) and AEO ($F_{3,43}$ = 4.74, p=0.006). The post-hoc LSD indicated that children had significantly larger offsets at both the start (Fig. 3A) and end (Fig. 3B) of movement than any of the other age groups.

B. *Perturbation Performance*

The perturbation trials allowed us to investigate whether differences in the use of on-line visual feedback occur across age groups and for different perturbation conditions.

An interaction between Condition and Group ($F_{9,129}$ = 2.934, p=0.003) was found for MT of the right hand. Children were significantly slower than all other groups in the NN, JN and JJ conditions (Fig. 4). However, they did have similar MTs to the older adults in the NJ condition. The young and middle adults had similar MTs across all conditions. Finally, the older adults were significantly slower than the young adults in the NN and NJ conditions only.

For MT of the left hand, main effects of group ($F_{3,43}$ = 6.04, p=0.002) and condition ($F_{3,129}$ =10.6, p<0.001) were found. The group main effect indicated that the children were significantly slower than the young and middle adults. No other significant differences were found (Fig. 5A). For the main effect of condition, results indicated that MTs for the left hand were significantly faster in the NN and JJ conditions than in the JN and NJ conditions (Fig. 5B).

When looking at coupling between the two hands during perturbation trials, a main effect of group ($F_{3,43}$ = 15.9, p<0.001) indicated that children had significantly larger offsets at movement initiation than any other age group (Fig. 6).

For the end of movement, a Group X Condition interaction ($F_{9,129}$ = 2.232, p=0.024) indicated that children had significantly larger offsets than all other groups in the NN condition (Fig. 7). The older adults had longer offsets than the young adults in the NJ condition. All groups had statistically similar offsets in the JN and JJ conditions.

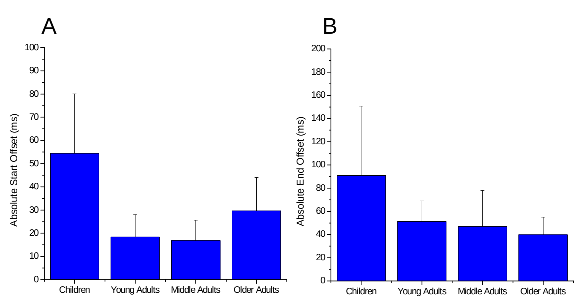

Figure 3. Main effect of Group on ASO and AEO

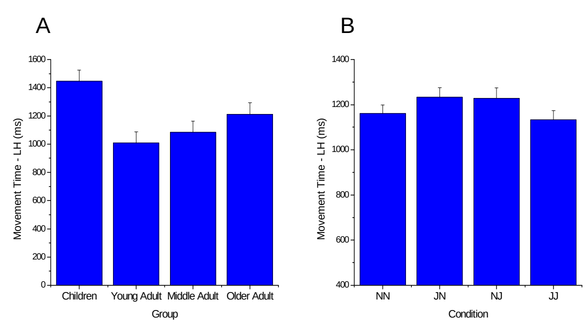

Figure 5. Main effects of Group and Condition on MT of the left hand

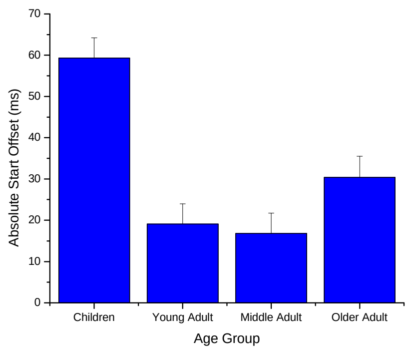

Figure 6. Main effect of Group on ASO

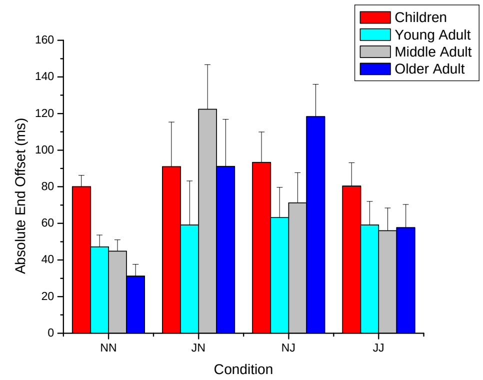

Figure 7. Main effect of Group on AEO

IV. Conclusion and Future Work

A. Performance of Bimanual Movements in VEs across the lifespan: Control and Perturbation Conditions

Each participant began the experiment by performing a block of simple bimanual trials without perturbation. These trials allowed us to determine whether age-specific patterns of bimanual performance in VEs are similar to the patterns seen in the natural environment. When considering overall MT, research in natural environments has indicated that children and the elderly typically complete both simple and complex tasks more slowly than young adults [23, 24]. A similar pattern of results was found in the current study, indicating some similarities between VEs and natural environments. With respect to bimanual coupling in natural environments, prior studies have indicated that both young children and older adults exhibit greater offsets at movement initiation and movement completion than young adults [24, 25]. These results were replicated for the children; however, the older adults used similar movement offset patterns as the young and middle adults. This difference in movement coupling for the elderly subjects suggests that they use different control strategies in natural compared to virtual environments. Timing differences between the hands in bimanual tasks have been associated with the requirement to shift visual attention between the targets to obtain sufficient feedback [19]. In older adults, slowing of visual sensory processing due to aging should result in even greater timing differences between the hands [22]. The smaller offsets seen in the current study suggests that the elderly subjects may have been relying on a predominantly feedforward strategy to complete the task instead of the typical feedback-based strategy that is seen in the natural environment. In a previous study investigating age differences on a simple reach-to-grasp task in a VE, we also found that older adults relied more heavily on a feedforward-based strategy [26]. The current findings add support to the notion that older adults may not rely on similar movement planning and execution strategies when performing tasks in VEs.

The perturbation conditions allowed us to investigate age differences in the visual control of movement in VEs. Overall, MT and offset results indicated similar movement performance between the ages of 18 and 50 years. These results suggest that design principles extracted from studies done on young adults may be applicable to middle-aged adults as well. In contrast, children and older adults exhibited distinct performance differences as a function of perturbation condition. While their performance was similar to the young and middle age groups for certain parameters and on certain conditions, the youngest and oldest age groups were slower and their movements were less coupled in other conditions. Overall, these results suggest that task conditions and age are critical factors when considering the design and functionality of VEs. Children and older adults do not perform or make use of sensory information in a similar fashion to young and middle-aged adults. Further, results are clearly task specific. This suggests that it is dangerous for designers to extrapolate performance in one task to other tasks. Instead, our results suggest that age-related performance must be investigated on a task by task basis for the generation of design principles.

B. Implications for the Design of Training and Rehabilitation VEs

Virtual environments have recently been touted as promising tools for training and rehabilitation [12, 13, 14]. However, the capacity for these environments to provide optimal benefits hinges on the learner's ability to transfer gains made in the VE to improvements in performance in the real world. It has long been known in the human motor learning literature that successful transfer occurs when similarities in movement strategies between the practice and performance environment are greatest [27]. In the current study we found that children, young, and middle-aged adults used similar bimanual strategies in the control condition to those reported for natural environments. In contrast the strategies used by the older adults in the VE were different than those reported in natural environments. It is important to note that visual feedback in this study was impoverished and relatively crude (i.e. no hand representation, simple table surface and object representation, low luminance contrast levels). These results suggest that when designing environments for older adults, it may be necessary to design tasks and environmental feedback conditions that better mimic the richness of the visual feedback conditions available in the real world. We are planning future studies to test this hypothesis.

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REFERENCES

[1] L.M. Howden and J.A. Meyer, "Age and Sex Composition 2010: Census Brief," Retrieved from URL http://www.census.gov/prod/cen2010/briefs/c2010br-03.pdf.

[2] European Commision, "Eurostat Population Projections," Retrieved from URL http://epp.eurostat.ec.europa.eu/portal/page/portal/population/data/main_tables.

[3] A. Dickinson, J. Arnott and S. Prior, "Methods for human-computer interaction research with older people," Behav Inform Technol, Vol. 26, No.4, July-August 2007, pp.343-352, DOI: 10.1080/01449290601176948.

[4] K. Günther, P. Schäfer, B. J. Holzner, G. W. Kemmler, "Long-term improvements in cognitive performance through computer-assisted cognitive training: A pilot study in a residential home for older people" Aging Ment Health, Vol. 7, No. 3, May 2003, pp. 200-206.

[5] D. Hawthorn, "Interface design and engagement with older people," Behav Inform Technol, Vol. 26, No. 4, 2007, pp. 333-41.

[6] M.W. Smith, J. Sharit, S.J. Czaja, "Aging, motor control, and the performance of computer mouse tasks," Hum Factors, Vol. 41, No. 3, Sep. 1999, pp. 389-396.

[7] B. Laursen, B.R. Jensen, A. Ratkevicius, "Performance and muscle activity during computer mouse tasks in young and elderly adults," Eur J Appl Physiol, Vol. 84, No. 4, Apr. 2001, pp. 329-336.

[8] A. Worden, N. Walker, K. Bharat, S. Hudson, "Making computers easier for older adults to use: area cursors and sticky icons," Proc of the SIGCHI conference on Human factors in computing systems (CHI '97), ACM Press, Apr. 1997, pg. 266-271.

[9] R.C. Allen, M.J. Singer, D.P. McDonald, J.E. Cotton, "Age differences in a virtual reality entertainment environment: A field study," Proc. 44th Annual Meeting of the Human Factors and Ergonomics Society (IEA/HFES 2000), Published by the Human Factors and Ergonomics Society, July 2000, pp. 542-545.

[10] F.A. McCreary, R.C. Williges, "Effects of Age and Field-of-View on Spatial Learning in an Immersive Virtual Environment" Proc 42nd Annual Meeting of the Human Factors and Ergonomics Society (HFES 1998), Published by the Human Factors and Ergonomics Society, Oct. 1998, pp. 1491-1495.

[11] D.P. McDonald, D.A. Vincenzi, R.V. Muldoon, R.R. Tyler, A.S. Barlow, and J.A. Smither, "Examination of age-related performance differences on a locomotion task in a virtual environment (abstract)," Proc. 42nd Annual Meeting of the Human Factors and Ergonomics Society (HFES 1998), Published by the Human Factors and Ergnomics Society, 1998.

[12] M.K. Holden, MK, "Virtual environments for motor rehabilitation: review" Cyberpsychol Behav, Vol. 8, June 2005, pp. 212-219.

[13] M. Wang, D. Reid, "Virtual reality in pediatric neurorehabilitation: attention deficit hyperactivity disorder, autism and cerebral palsy," Neuroepidemiology, Vol. 36, No. 1, Nov. 2010, pp. 2-18.

[14] S. Bermúdez i Badia, M. da Silva Cameirão, "The Neurorehabilitation Training Toolkit (NTT): a Novel Worldwide Accessible Motor Training Approach for at-Home Rehabilitation after Stroke" Stroke Res Treat, Vol. 2012, Article ID 802157, 13 pages, 2012. doi:10.1155/2012/802157

[15] J.H. Cauraugh, S.B. Kim, A. Duley, "Coupled bilateral movements and active neuromuscular stimulation: intralimb transfer evidence during bimanual aiming," Neurosci Lett, Vol. 382, 2005, pp. 39-44

[16] A.H. Mason, "Coordination and control of bimanual prehension: Effects of perturbing object location," Exp Brain Res, Vol. 188, No. 1, 2008, pp. 125-139.

[17] J.A.S. Kelso, D.L. Southard, and D. Goodman, "On the coordination of two-handed movements," J Exp Psychol: Hum Percept Perform, Vol. 5, 1979, pp. 229-238

[18] G.M. Jackson, S.R. Jackson, and A. Kritikos, (1999). "Attention for action: Coordination of bimanual reach-to-grasp movements," Brit J Psychol, Vol. 90, 1999, pp. 247–270.

[19] G.P. Bingham, K. Hughes, and M. Mon-Williams, "The coordination patterns observed when the hands reach-to-grasp separate objects," Exp Brain Res, Vol. 184, 2008, pp. 283–293.

[20] J. Diedrichsen, R. Nambisan, S. Kennerley, R.B. Ivry, "Independent on-line control of the two hands during bimanual reaching," Eur J Neurosci, Vol 19, 2004, pp. 1643–1652.

[21] P.J. Sparto, M.S. Redfern, J.G. Jasko, M.L. Casselbrant, E.M. Mandel, J.M. Furman, "The influence of dynamic visual cues for postural control in children aged 7-12 years," Exp Brain Res, Vol. 168, Jan. 2006, pp. 505-516.

[22] S. Chaput, L. Proteau, "Aging and motor control," J Gerontol B Psychol Sci Soc Sci, Vol. 51, Nov. 1996, pp. 346-355.

[23] S. Zoia, E. Pezzetta, L. Blason, A. Scabar, M. Carrozzi, M. Bulgheroni, and U. Castiello, "A comparison of the reach-to-grasp movements between children and adults: a kinematic study," Dev Neuropsychol, Vol. 30, 2006, pp 719–738.

[24] G.E. Stelmach, P.C. Amrein, N.L. Goggin, "Age differences in bimanual coordination," J Gerontol, Vol. 43, Jan 1988, pp 18-23.

[25] A.H. Mason, J.L. Bruyn, J.C. Lazarus, "Bimanual coordination in children: Manipulation of object distance", J. Sport Exer Pscyhol, Vol. 34, suppl., 2012, p. s110.

[26] P.J. Grabowski and A.H. Mason, "Vision for Motor Performance in Virtual Environments Across the Lifespan," In Virtual Reality and Environments, Cecilia Sik Lanyi, Ed. Croatia: InTech Press, 2012, ISBN: 978-953-51-0579-4.

[27] R.A. Magill (2011) Motor Learning and control: Concepts and Applications (9th edition), New York, McGraw-Hill.