Kinematic Description of Bimanual Performance in Unpredictable Virtual Environments

A Lifespan Study

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***Abstract*— Immersive virtual environments show great promise for use in applications such as design and prototyping, data visualization, and rehabilitation of motor impairments. However, our understanding of how people of various ages process and use sensory information to complete tasks within these environments is limited. The purpose of the research described here was to characterize motor performance in virtual environments across the lifespan on simple, foundational skills. Our results indicated that children and older adults used different strategies when performing the task when compared to young adults. While older adults adjusted for the virtual environment by planning a slower movement, children compensated for the artificial environment by relying on feedback to a greater extent. Movement strategies for the youngest and oldest groups were also different in the virtual environment when compared to results from natural environment experiments. We conclude that children and older adults do not plan movements or make use of sensory information in a similar fashion to young and middle-aged adults when performing in a virtual environment. The design implications of these results are related to differences in needed sensory information between children, young and older adults, the transfer of training effects between virtual and real environments, and important differences between performance and learning applications.**

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

I. Introduction

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. The purpose of the research reported here is to begin to fill this large gap in knowledge by determining how the age of the user influences motor performance in virtual environments. In [1], we asked children, young adults, middle age adults and older adult participants to perform simple and bimanual reach to grasp movements, and movements where targets were visually displaced. We found that children and older adults used different strategies when performing reach to grasp tasks in a virtual environment when compared to young adults. Specifically, older adults adjusted for the virtual environment by planning a slower movement, while children compensated for the artificial environment by relying on feedback to a greater extent. In the current paper we extend on [1] by including a more detailed literature review, additional and detailed kinematic analyses and a more thorough discussion of the implication of these results.

The structure of this paper is as follows. In Section II we present a thorough review of the literature upon which this work is motivated. In Section III we describe the experimental method used in this paper to investigate the roles of age and vision on the performance of reach to grasp movements in virtual environments. In Section IV, the results of the statistical analyses are presented and finally, in Section V the results are discussed in the context of the current state of knowledge and potential applications/implications of this work.

II. Review of Literature

To adequately frame the theory and methods used in the research study presented here, this review of literature first covers recent work on the influence of age on human computer interaction (Section A). Next, we review the current knowledge regarding the control of simple and bimanual movements in both natural and computer generated environments (Section B) as well as the motivation behind using a perturbation task in this study (Section C). Finally, in Section D we present the hypotheses for the current study.

A. HCI and Age

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 [2]. 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 [3]. Still most HCI research is focused on younger people, often university or college students [4]. 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.

In order to understand how age may influence performance on tasks requiring human-computer interaction, we must first take a step back and understand the influence of age on movement performance in general. The human body is a constantly changing entity throughout the lifespan and all systems of the human body, including the sensorimotor system, undergo changes. Movement programming functions are organized quite differently in children than in young adults [5], [6]. Further studies have shown that children process sensory information from visual and proprioceptive receptors differently than adults [7], [8]. Children tend to rely on visual feedback to a greater extent [9]. There is also a general indication that both the processing of afferent information, or incoming signals to the central nervous system (CNS), and the production of efferent information, or outgoing commands, steadily changes as a function of age in the developing human. Once beyond the "development" stage of the lifespan, into older adulthood, the volume of research on age-related changes greatly expands. Multiple authors demonstrate physical changes in brain tissues [10]-[12], changes in the activation of motor neurons in the brain [13], and a general loss of nerve tissue [11], [12]. These tissue changes then result in myriad functional declines within the CNS. There is a general deterioration of motor planning [14], [15] and anticipatory control [16], as well as slowing of central processing [17]-[20].

These transformations in the sensorimotor system have a resultant effect on motor performance in daily life. Children tend to show less accuracy, decreased smoothness of movement, and decreased speed when compared to young adults [21]. Many of these same manifestations become apparent as adults age. According to Schut [22], most physiologic processes begin to decline at a rate of 1% per year beginning at age 30. In general, aging adults demonstrate decreases in movement speed [14], [18], accuracy [17], strength [23], hand dexterity [24], and postural control [25], and increases in reaction time.

So, how do these lifespan changes in information processing within the CNS affect humans as they use computer interfaces? 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., [26], [27]), or on the age-appropriate design of input devices (e.g., [28]-[31]). There is also a modest body of scientific literature which explores the areas of motor control in human computer interaction (HCI) as a function of age [27], [29]. Most of this information centers on the input device, specifically mouse usage in children and older adults. It is reported that there are many age-related changes, and in general it is quite difficult for children and older individuals to use a mouse [27], [28]. Maintaining adequate pressure and the act of double-clicking seem to consistently be the most problematic. Difficulty with cursor control is named as a top complaint among older individuals [4], [26]. It has also been shown that performance within a standard computer interface is slower and results in a greater number of errors with increased age of the operator.

Much less is known about how age influences performance within immersive three-dimensional (3-D) virtual environments (VEs) [32]-[34]. 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, education, 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 [35], [36]. 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 [32]-[34]. According to Allen et al. [32], "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 [37]. 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 [38].

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 [39]. 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 [40], [41]. 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 [40], [41]. However, timing differences between the hands have been shown, and results indicate that these differences are associated with insufficient visual feedback for movement control [42]. 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 [43] and virtual environments [39] 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 [44], [45] 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.

D. Hypotheses

We asked participants ranging from 7 to 90 years of age to perform bimanual reach to grasp movements in a virtual environment. In the first set of trials, target objects remained at their initial position throughout the task, giving us a baseline performance for each participant. Based on previous literature on age differences and motor performance, we expected that younger children and older adults would perform the bimanual tasks more slowly than the young adults. Further, we expected that temporal synchronization between the two hands would be less strong in the youngest and oldest participants due to their reliance on visual feedback. These results would replicate the results of studies performed in natural environments. When considering performance in the perturbation conditions, we expected the youngest and oldest participants to show a decreased ability to respond to the visual displacement of the target when compared to the young adults. Specifically, it is known that young children and the elderly process sensory/visual information more slowly than young adults [21], [22]. Since responding to the perturbation relies on the speed of visual information processing, we hypothesized that children and older adults would respond more slowly and would show less coordinated movements in the perturbed conditions than the young adults.

III. METHOD

In the following section we detail the method used to determine how age influences performance in virtual environments. We begin by describing our participant pool and the experimental apparatus. Next we describe the tasks performed by each participant. Finally we describe our data analysis methods.

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 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 have 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 (Fig. 1). In this environment, subjects see three-dimensional graphical representations of target objects but interact with physical objects. 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 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 to generate the superimposed graphical representations of the cubes. The lag between motion of the LED and its graphical representation was indiscernible to participants. 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.

Figure 1. Experimental apparatus.

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 grasp (i.e., index finger and thumb only) and participants were asked to move at a comfortable pace once the target cubes appeared.

Participants experienced trials in four experimental conditions. As shown in Fig. 2, in the control condition both targets remained at their initial location throughout the trial (left target no jump/right target no jump; NN). As shown in Fig. 3, 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

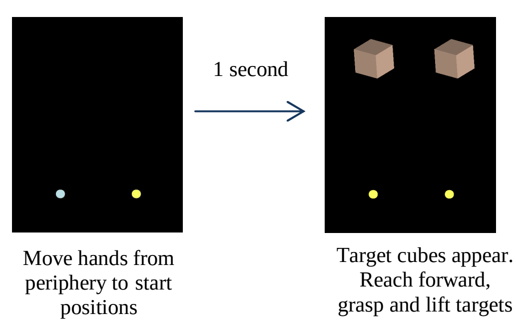

Figure 2. Time course a control trial (top-down view).

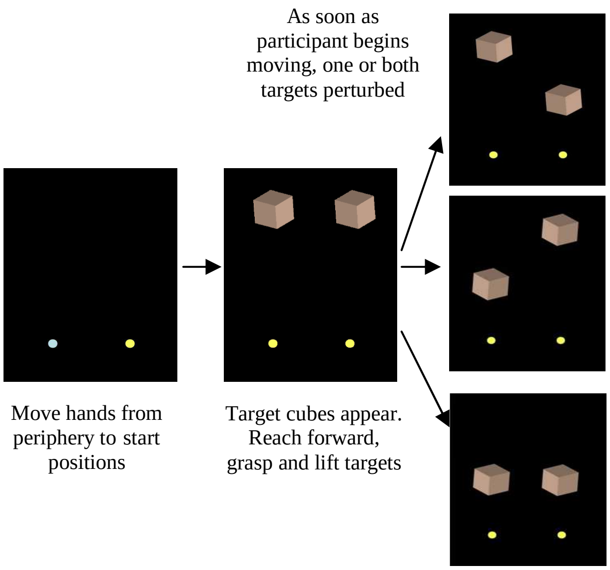

Figure 3. Time course of perturbation trials (top down view).

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

Human motor control, biomechanics and neuroscience research has provided a comprehensive description of how humans reach to grasp and manipulate objects in natural environments under a variety of sensory and environmental conditions. By using the same measurement techniques as those employed to monitor human performance in natural environments, we can compare movement in virtual environments to decades of existing human performance literature. The comparisons allow us to develop comprehensive cognitive models of human performance under various sensory feedback conditions. Simple timing measures such as movement time provide a general description of upper limb movements. However, in motor control studies, more complex 3-D kinematic measures such as displacement profiles, movement velocity, deceleration time, and the formation of the grasp aperture (resultant distance between the index finger and thumb for a precision pinch grip) have also been used to characterize object acquisition movements. By observing regularities in the 3-D kinematic and kinetic information, inferences can be made regarding how movements are planned and performed by the neurocontrol system.

Peak velocity can be used to measure the open-loop processes occurring during target acquisition tasks and is thought to reflect motor planning. In contrast, the time from peak velocity represented as a percentage of movement time can be used as a measure of closed-loop control, where a longer time spent decelerating toward the target is equated with a greater reliance on feedback. These measures combined with movement time allow us to completely describe a target acquisition task in terms of open and closed loop control.

For tasks that involve grasping objects, a measure of the opening and closing of the hand is also required. Aperture can be used to quantify grasp formation. In human performance literature larger apertures have been associated with more complex tasks that demand greater attentional resources [46]. It is believed that a larger aperture is used as a compensatory strategy to avoid missing or hitting the target. This detailed movement information essentially provides a window into the motor control system and allows the determination of what sensory feedback characteristics are important for movement planning and production.

We quantified the above kinematic measures of movement using position data from the block LED as well as LEDs on the wrists of both hands. Start of movement was defined as the point where resultant 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 vertical 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. The position data were differentiated and peak resultant velocity (PV) was extracted. Percent time from peak velocity (PTFPV) was defined as (MT – Time of peak velocity)/MT * 100. 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). To quantify the grasp, we extracted the peak aperture (PA) achieved by the index finger and thumb of each hand during the course of the movement.

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, PV, PTFPV and PA.

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, JN, NJ, 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 $p < 0.05$.

IV. RESULTS

The results of our statistical analyses are shown in the following sections. In Section A we present the results for the initial set of bimanual control trials that each participant performed at the beginning of the experimental session. In Section B we present the results for trials where the target could be displaced unexpectedly (i.e., perturbed).

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. Typical velocity profiles for children, young adults (middle adults resembled young adults) and older adults in the control condition are shown in Fig. 4A. Note that velocities are higher for the children and young adults than the older adults. Also note that movement times (as indicated by the end of the trace on the time axis) are longer for the children and older adults than the young adults. Finally, note that velocity profiles for the young and older adults appear smoother than those produced by the children. The decreased smoothness represented in the children's profiles reflects a greater reliance on sensory feedback and error correction during movement production. Results of the statistical analyses on the individual kinematic measures are presented below.

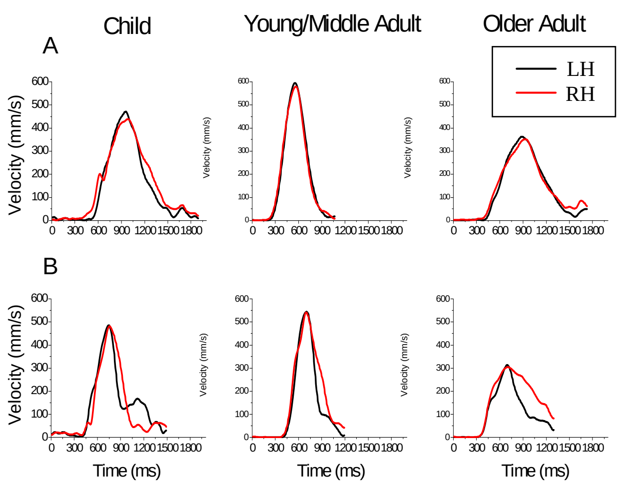

Figure 4. Typical velocity profiles for the children, young/middle adults and older adults in the A) NN condition, B) JN condition.

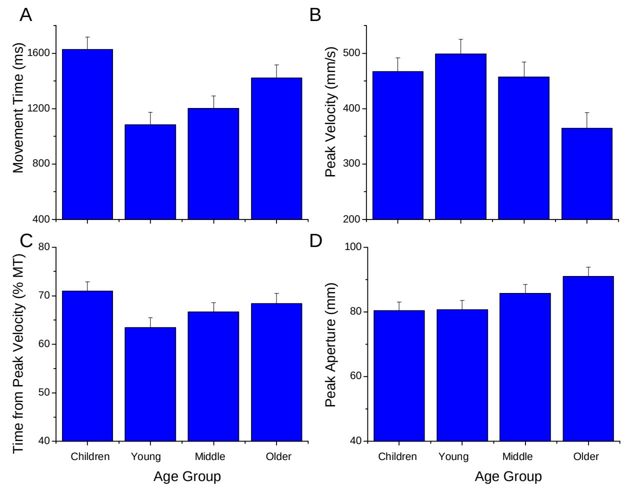

Figure 5. Main effect of Group on movement time, peak velocity, time from peak velocity as a percent of movement time and peak aperture in the control condition.

Main effects of Group were found for movement time ($F_{3,43}$ = 7.053, p=0.001), peak velocity ($F_{3,43}$ = 4.335, p=0.01), and peak aperture ($F_{3,43}$ = 3.2, p=0.033). The main effect of Group for percent time from peak velocity was marginally significant ($F_{3,43}$ = 4.335, p=0.06). 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. 5A). Further decomposition of the movement into its velocity profile indicated that the longer movement time used by the older adults was the result of a significantly lower peak reaching velocity when compared to all other groups (p<0.05). In contrast, the children achieved a similar peak reaching velocity as the young and middle aged adults (Fig. 5B). For the children, the additional movement time when compared to the young adults came as the result of a longer time spent decelerating toward the target (p=0.09)(Fig. 5C). In contrast, the older adults spent a similar proportion of the movement decelerating toward the target as the middle-aged and young adults (p>0.05). These results suggest that although both the children and older adults perform the reach to grasp task more slowly than the young adults, the reason for this slowing is different for the two age groups. Finally, when considering grasp aperture, results indicated that the older adults produced a significantly larger hand opening when reaching for the targets than the young adults (p<0.05). In contrast, the aperture used by the children was similar to the young adults (Fig. 5D)

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-

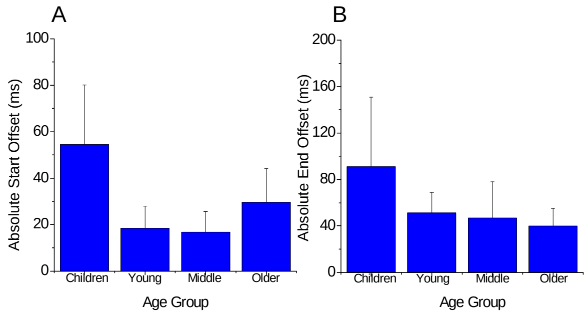

Figure 6. Main effect of Group on ASO and AEO.

hoc LSD indicated that children had significantly larger offsets at both the start (Fig. 6A) and end (Fig. 6B) 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. Fig. 4B shows velocity profiles for the right and left hand in the JN condition for the children, young adults and older adults. First note that the young adults adjust smoothly to the perturbation and efficiently decouple the movements of the two hands to effectively grasp the perturbed target at its new location. In contrast, note that the children produce velocity profiles that are less smooth and efficient. These profiles provide evidence that the children have greater difficulty making use of online sensory information when reorganizing for the perturbation. For the older adults, note the much lower peak velocity. This suggests that older adults pre-plan a more conservative movement.

We analyzed the data separately for the right and left hands to simplify interpretation. An interaction between Condition and Group ($F_{9,129}$ = 2.934, p=0.003) was found for MT of the right hand. Children had significantly longer MTs than all other groups in the NN, JN and JJ conditions (Fig. 7A). 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 but the older adults were significantly slower than the young adults in the NN and NJ conditions only. Further decomposition of the movement of the right hand into its velocity profile revealed a main effect of Condition ($F_{3,129}$ =12.5, p<0.001) and Group ($F_{3,43}$ = 2.75, p=0.055) for peak velocity. Velocities were highest in the NN condition (474.5 ± 14 mm/s), lowest in the JJ condition (438.5 ± 14 mm/s) and moderate when only one target was perturbed (JN = 456.3 ± 15 mm/s; NJ = 453.0 ± 15.7 mm/s). The main effect of Group indicated that older adults had significantly lower peak velocities than the young adults (Fig. 7B).

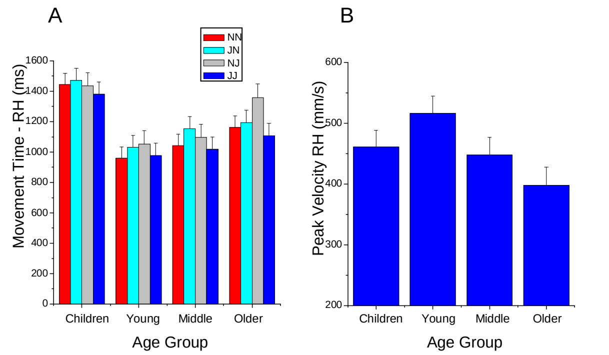

Figure 7. Group X Condition interaction for MT and main effect of Group for peak velocity of the right hand.

When considering how participants used visual feedback to decelerate toward the target, an interaction between Condition and Group ($F_{9,129}$ = 2.0, p=0.045) was found for the right hand. As seen in Fig. 8, children had longer deceleration times than the three other age groups in all conditions except NJ.

Finally, for the grasp portion of the movement, main effects of Group ($F_{3,43}$ = 5.8, p=0.002) and Condition ($F_{3,129}$ =2.8, p<0.044) were found for peak aperture for the right hand. The main effect of Group indicated that peak apertures were larger for the older adults (92.3 ± 3 mm) than the three other groups (children = 77.4 ± 2.5 mm; young adult = 80.3 ± 2.7 mm; middle adult = 81.2 ± 2.7 mm). The main effect of Condition indicated that peak apertures were larger when neither object was perturbed (83.7 ± 1.2 mm) when compared to the other three conditions (JJ = 82.0 ± 1.3 mm; JN = 82.5 ± 1.5 mm; NJ = 83.0 ± 1.4 mm).

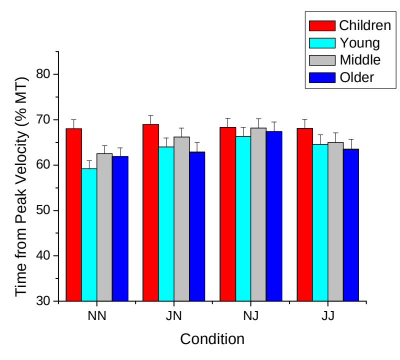

Figure 8. Interaction between Condition and Group for deceleration time of the right hand.

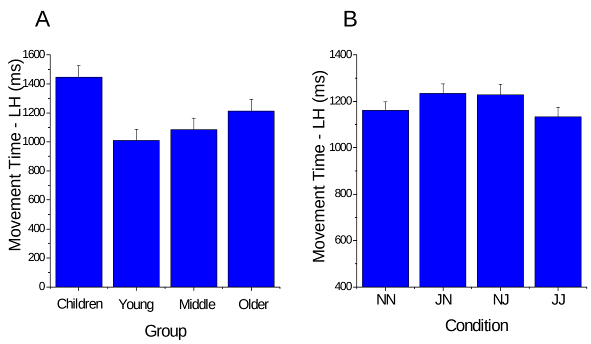

Figure 9. Main effects of Group and Condition on MT of the left hand.

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. 9A). 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. 9B).

Decomposition of movement time into kinematic features indicated a main effect of Condition ($F_{3,129}$ =17.1, p<0.001) and a marginally significant main effect of Group ($F_{3,43}$ = 2.4, p<0.082) for peak velocity. The Group effect revealed lower peak velocities for the older adults (397.4 ± 30.5 mm/s) when compared to the young adults (508.7 ± 29 mm/s) (p < 0.05). Peak velocities for the children (440.5 ± 28 mm/s) and middle adults (454.2 ± 29 mm/s) were similar to all other groups. The main effect of Condition revealed higher peak velocities in the NN condition (468.3 ± 14 mm/s) than all other conditions (JJ = 432.7 ± 15; JN = 439.7 ± 146; NJ = 460.1 ± 15 mm/s). An interaction between Group X Condition ($F_{3,43}$ = 2.1, p<0.03) was also found for deceleration time (see Fig. 10). As with the right hand, these results indicated that children had longer deceleration times than the young and older adults in all conditions.

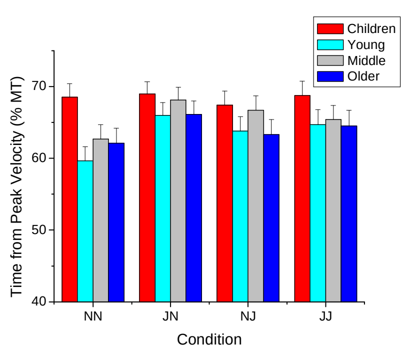

Figure 10. Interaction between Condition and Group for deceleration time of the left hand.

For the grasp portion of the movement main effects of Group ($F_{3,43}$ = 6.9, p=0.001) and Condition ($F_{3,129}$ = 3.3, p<0.02) were found for peak aperture of the left hand. The main effect of Group indicated that peak apertures were larger for the older adults (92.1 ± 3 mm) and middle age adults (86.2 ± 2.5 mm) than the young adults (79.2 ± 2 mm) and children (77.8 ± 2 mm). The main effect of Condition indicated that peak apertures were larger when neither object was perturbed (84.7 ± 1.2 mm) or when the right object was perturbed (84.4 ± 1.2) than the other two conditions (JJ = 83.0 ± 1.4 mm; JN = 83.2 ± 1.4 mm).

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. 11). 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. 12). 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.

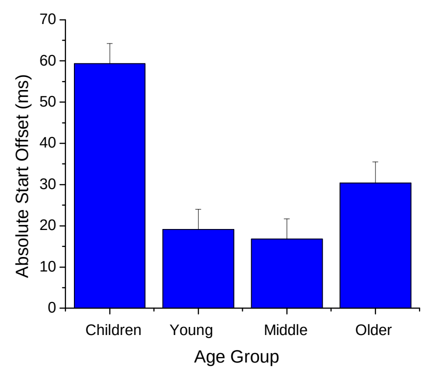

Figure 11. Main effect of Group on ASO of the left hand.

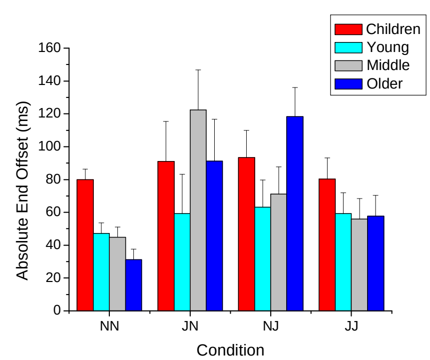

Figure 12. Main effect of Group on AEO.

V. 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 [47], [48]. 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 [49], [50]. 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 [42]. In older adults, slowing of visual sensory processing due to aging should result in even greater timing differences between the hands [45]. The smaller offsets seen in the current study suggest 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 natural environments. This conclusion is supported by the detailed kinematic measures reported in this study. In particular, peak velocity, which is typically reached early in the movement, can be used as a measure of movement planning. Older adults used a lower peak velocity in the control trials than subjects in all other groups. This suggests that the older adults were in fact using feed-forward planning to execute a cautious reach strategy in our virtual environment. The larger grasp apertures used by the older adults also support the notion of a cautious reaching strategy.

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 [50]. Deceleration time results for the older adults also indicated that they spent a similar time using sensory information to home-in on the target as the younger adults. In contrast, results from reach-to-grasp studies in natural environments have indicated that elderly participants typically use longer deceleration times than their younger counterparts [51]. Again, this points to a difference in strategy in the virtual environment when compared to natural environments. We hypothesize that the impoverished and unnatural feedback available in the virtual environment may have made this feedback less useful to the older adults. Therefore, 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 when compared to similar tasks in a natural environment.

Unlike the older adults, the children appear to use similar strategies in both virtual and natural environments for bimanual grasping. Specifically, it has been found that children tend to rely heavily on sensory feedback when grasping objects in natural environments [9]. In the current study, children produced peak reaching velocities that were similar to the young adults, yet their movement times were slower. These longer movement times were the result of an increased amount of time spent decelerating toward the target. Increased deceleration times can be used to infer a greater reliance on sensory information. Since sensory feedback is important for movement execution in children, our results suggest that providing an enriched sensory experience may improve their overall performance in VEs. Of interest in future work will be to determine whether children can achieve higher levels of performance in VEs if sensory information is enhanced/augmented when compared to natural environments. This could have significant implications with respect to motor skill learning for interaction tasks.

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. Further, the children continued to show an increased reliance on sensory feedback (i.e., longer deceleration times) whereas the older adults continued to rely on cautious movement planning (i.e., lower peak velocities). 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 plan movements 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 [35]-[37]. A key consideration when designing a fully immersive virtual environment is that all sensory information provided to the user must be synthetically generated. As such, designers must make informed decisions about what sensory information to provide to the user and when that information should be provided. Several studies have been conducted to determine how to effectively provide sensory information to users for the performance of simple tasks in VEs [52]-[54]. Unfortunately, many of those studies have focused exclusively on the performance of young adults. As we begin to consider the multitude of applications for which VEs show promise, it is clear that users of all ages need to be considered (i.e., education and rehabilitation). The results of this study allow us to make concrete suggestions to designers of VEs. These relate to differences in needed sensory information between children, young and older adults, the transfer of training effects between virtual and real environments, and important differences between performance and learning applications.

Research has shown striking differences in the use of sensory feedback by children, young adults and the elderly as they perform motor tasks in natural environments [7],[8],[14]. Results of the current study replicate those findings and extend them to virtual environments. These findings suggest that designers of virtual environments may want to consider enhancing sensory feedback provided to the youngest and oldest users of virtual environments as a method of improving performance in those age groups. Grabowski & Mason [50] found that elderly participants performed simple reach to grasp tasks more effectively when luminance contrast was increased in the visual display. In contrast, young adult participants experienced a point of diminishing returns. Our current results and the results of this previous work suggest that sensory information tailored to a participant's age could lead to superior performance in virtual environments.

When considering education and rehabilitation applications, the capacity for virtual environments to enhance learning hinges on the user'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 [55]. This phenomenon is called the encoding specificity principle [55]. 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. This indicates that the sensory information available in our setup was sufficient to produce "normal" motor performance in the younger participant groups and could lead to positive transfer between the virtual and real environments. In contrast the strategies used by the older adults in the VE were different than those reported in natural environments. These results suggest that the sensory characteristics present in our virtual environment did not sufficiently mimic natural environment conditions for our elderly participants. 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 visual feedback conditions available in the real world in order to elicit positive transfer between the two environments. In contrast, younger participants may see positive transfer with less realistic visual feedback conditions.

Finally, it is important to consider an apparent contradiction between the two previously mentioned implications. Specifically, we first suggested that designers may want to enhance the sensory feedback available in the virtual environment for younger and older participants. These enhancements could lead to sensory feedback that is more detailed and easily processed than what is available in natural environments (i.e., increased luminance contrast). Our next suggestion implies that sensory feedback may need to perfectly mimic what is available in natural environments in order to ensure positive transfer in learning applications for older users. This contradiction illustrates a third point that designers need to consider when determining how to provide sensory feedback; the task or application. It is clear that sensory feedback needs to be tailored, not only to the age of the user, but also to the application at hand. Specifically, applications that are performance based may benefit from sensory information that surpasses what is available in natural environments, whereas learning/transfer applications may need to better mimic the real world. A compromise between these two suggestions may be to use a "fading" technique where sensory feedback is initially enhanced to elicit improved performance but is faded during practice towards more realistic levels to enhance transfer of learned skills [55]. We are planning future studies to test this hypothesis.

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