EFFECTS OF AGE AND EXPERIENCE ON MEMORY-GUIDED MOVEMENTS

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The purpose of the present research was threefold: 1) to investigate whether natural aging affects the movements to remembered targets when participants make reaching movements under closed-loop feedback conditions, 2) to determine if experience with visually-guided movements facilitates memory-guided reaching and 3) to determine if age affects this facilitation. Two groups of 10 participants (healthy older and healthy younger) performed a manual aiming task with a mouse on a graphics tablet. A target appeared in one of 6 possible locations on a computer screen and participants had to make aiming movements with a visible cursor in 3 different visual conditions: full vision, immediate recall and delayed recall. In the full vision condition vision of the target was available throughout the movement. In the delay conditions the target disappeared either at the initiation of the aiming movement (immediate recall) or 2 seconds before movement onset (delayed recall). Vision of the hand (cursor) was available in all conditions. Each memory condition was divided into 2 blocks; block 1 was presented before the full vision condition and block 2 was presented after. Endpoint accuracy and variability were measured along with movement kinematics. Results showed no age differences in the kinematics in the full vision condition. For memory dependent pointing age also did not affect the movement kinematics or endpoint accuracy. Movements to remembered targets were significantly more variable in the delay recall compared to the immediate recall condition. A Block by Condition effect showed that the delay effect was present in the first block, but not in the second block, suggesting that variability did not increase with memory delay once participants had experience from full vision reaching. A Group by Condition effect showed the older adults were more variable than younger, although this difference was smaller in the delay condition due to the increase in variability as a function of delay seen in younger but not older adults. These findings suggest that aging does not affect how movements are controlled whether pointing to visible or remembered targets. They also suggest that aging does not affect the accuracy in pointing to remembered targets. Aging does affect the variability of these pointing movements. Finally, experience in pointing at targets with full vision modulates the increase in variability of pointing as a function of delay.

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Introduction

One of the most frequent movements we make in our daily lives is reaching for or pointing to objects and other targets in our environment. In most cases these targets remain visible during the course of our reaching movement, but sometimes, the target may not be visible. An example of such an occurrence is when we avert our gaze away from the target to something else in our environment or when the ambient lighting is extinguished as might happen if the lights are turned off. One of the questions of interest in this thesis is how these movements to a remembered target location differ in terms of their accuracy and the way they are controlled, from those where the target is constantly visible. A second issue we address is how age affects movements to visible versus remembered targets.

In addressing these questions we begin by reviewing the literature on how visually-guided aiming movements are controlled and how aging affects these control processes. We will then examine how visually-guided movements compare to memory-guided movements in terms of their accuracy and control. Finally we will report on an experiment designed to examine these questions.

Control of Movements to Continuously Visible Targets

Effective movement control is accomplished by adjusting a motor plan according to information in the form of feedback provided by one's environment. Two primary modes of movement control are closed-loop and open-loop. Open-loop movement control is generated from central planning which depends highly on feedforward processing based on motor programs selected prior to movement initiation. Faster movements may operate more in terms of open-loop control for stages of movement execution because there is less time to evaluate and process the differences between the limb's position relative to the movement endpoint. Closed-loop control depends very highly on taking visual, proprioceptive or other forms of sensory information and correcting a movement based on the disparities between the actual movement and the intended movement. Feedback based online closed-loop control runs in real-time where the status of the movement is constantly being updated to make comparisons about the current limb position relative to the desired endpoint. Reaching movements also tend to be more accurate when made in an environment where visual feedback of the target is available (Keele and Posner, 1968).

Typically when vision is provided in a closed-loop setting, the direction and length of the movement to a target determines the kinematics as well. It has been well established that movements to targets with larger amplitudes have different kinematic profiles than movements to targets with smaller amplitudes. Fitts' law predicts that movement time is a linear function of the index of difficulty of aiming to a target. One of the factors that determine the index of difficulty is the amplitude (Fitts, 1954). Therefore, researchers agree that movements with larger amplitudes yield longer movement times, higher peak velocities and more time spent in deceleration compared to movements with smaller amplitudes (MacKenzie, Marteniuk, Dugas, and Liske, 1987; Roy, Weir, Desjardins-Denault, Winchester, 1999; Elliott and Madalena, 1986; Messier and Kalaska, 1999). Also, the position or location of the target relative to the midline axis of the body can affect the way the movement is performed depending on the hand that is used for reaching. Movements made into contralateral hemispace relative to the reaching hand, have longer movement times and lower peak velocities compared to movements made in ipsilateral hemispace (Roy, Kalbfleisch, and Silcher, 1999).

Movements to Remembered Targets

Memory-based movements can be influenced by various factors that cannot only affect the accuracy, but the control of the movement, such as the peak velocity or the proportion of the movement spent in deceleration, as well. When vision of a target is restricted, as in an open-loop control setting, there are a number of processes that must compensate for the lack of visual information of the movement endpoint. There are several studies that support the theory of a visual representation of the target, which is stored in memory so that an appropriate motor program can be generated. One of the most pivotal, and most frequently cited is one by Elliott and Madalena (1987) where they examined movements made to one of two midline targets (25 and 35 cm away from a home position) in five visual conditions; full vision, and no vision with a delay of 0, 2, 5, or 10 seconds. In the full vision condition the lights were kept on for the entire trial allowing the participant vision of their limb and the target during the movement. In the 0 second delay condition, the lights were extinguished immediately after the subject left the home position. For the remainder of the delay conditions, the participant was given as much encoding time as they needed before notifying the experimenter to extinguish the lights. The experimenter then verbally informed participants when to initiate the movement based on the appropriate delay time of the trial (2, 5 or 10 seconds). Within each visual reaching condition, they also imposed two different movement times; fast (200-300 ms) and slow (400-500 ms).

They found no significant difference in the total amplitude and directional error between the full vision and no vision-0 second delay condition and found that both of these conditions had significantly less error than the other no vision delay conditions. They also found that fast movements were less accurate than slow movements in the full vision condition and the error in the 2 and 5 second delays was affected more by a fast movement time than the slow movement time as the error was greater in the fast movement time. The difference between the full vision and no vision-0 second delay condition with the other no vision delay conditions prompted the authors to propose that once vision of a target has been eliminated, a '*highly accurate'* visual representation remains stored in memory for a brief period of time so that a movement can be properly executed. They also proposed that this memory-stored representation is temporally sensitive and deteriorates within a time frame of two seconds.

Other studies have attempted to reproduce and further elaborate on Elliott and Madalena's findings. Westwood, Heath and Roy (2001) conducted a similar study to Elliott and Madalena's where participants made reaching movements to 5 midline targets. Visual conditions were controlled by liquid crystal shutter goggles in 6 visual conditions; full vision, open-loop, and no vision with delays of 500, 1,000, 1,500 and 2,000 ms. In all conditions there was a preview phase of 2 seconds where the target was visible and an auditory cue signaled the participant to initiate the movement. There was vision of both the target and the limb in the full vision condition. The open-loop condition consisted of the auditory cue signaling movement initiation sounding at the same time as the goggles went to their opaque state. In the various delay conditions, the goggles would turn opaque after the preview phase and the auditory cue would sound after the appropriate delay time.

Results showed that the radial error was significantly greater in the open-loop condition compared to the full vision condition, both of which were significantly smaller than all delay conditions, which did not differ from each other. The results were quite similar to those of Elliott and Madalena, however, the authors' major contribution was the finding that delays as brief as 500ms were enough to influence the quality of the proposed visual representation.

Westwood and colleagues did another study (2003) examining the quality of the *"highly accurate"* visual representation proposed by Elliott and Madalena. They argued that if Elliott and Madalena's hypothesis was correct, the systematic and variable error would be similar for an open-loop and brief-delay condition. They conducted a similar experiment to their previous study using 4 visual conditions; open-loop, where vision was occluded at movement onset, brief delay (virtually 0 second delay), where vision was occluded coincidentally with the auditory cue that signaled movement initiation, and 500 ms and 2,000 ms delays where the target was occluded and the auditory cue signaled movement initiation after either 500 or 2,000 ms.

They found that the systematic error (mean position at movement offset relative to actual target position) in the primary movement axis was the highest in the open-loop visual condition and was greatly reduced in the brief delay condition and again in the 500 ms delay condition. The variable error in the primary movement axis was the lowest in the open-loop condition and increased in the brief-delay condition and again in the 2,000 ms delay condition. Westwood and colleagues concluded that these results were inconsistent with Elliott and Madalena's hypothesis because variability was greater for the brief delay condition than for the open-loop condition, which differed only in terms of whether vision was available during the reaction time portion of the movement. They argued that because of this finding, the motor system does not have access to a highly accurate representation of the target in the aiming environment. They also argue that reaching movements are programmed just prior to movement initiation and not before and that the movements are based on up-to-date visual information about the target in a viewer-based, or egocentric, frame of reference. Since egocentric coordinates change quite quickly and can be unpredictable during a reaching movement, the stored target information would quickly become outdated and therefore less reliable which would account for the high variable error in the brief delay condition of the experiment.

It should be understood that the experimental protocol in many of the studies investigating movements to remembered targets involve reaching in an open-loop paradigm, where the participant not only has no visual information about the target, but they are not provided with visual information of the limb during the movement. Very few studies have investigated memory-dependent reaching in an environment where vision of the hand is provided.

One of the most recent experiments done in this area was a study by Heath (2005) in which he examined the differences between memory-guided reaching movements made in both open and closed-loop conditions. Participants were instructed to make reaching movements with their right hand to one of two targets located either 28 cm (close) or 38 cm (far) to the right of a home position in two reaching conditions; a limb visible (closed loop) condition and a limb occluded (open-loop) condition. In the limb visible condition, participants had vision of their virtual hand by way of light emitting diodes (LEDs) attached to the pointing (index) finger. This provided participants with continuous vision of their moving limb. In the limb-occluded condition, the LEDs were extinguished once the movement was initiated. Within each reaching condition, there were six visual conditions, which included target vision (T-V), target open-loop (T-OL), and target delay conditions of 0, 500, 1,500, and 2,500 ms (TD-0, TD-500, TD-1, 500, TD-2, 500). There was a preview phase of 2 seconds where the target was presented followed by an auditory cue signaling the participant to initiate the movement. In the T-V condition, the target remained visible throughout the movement and in the T-OL condition the target was occluded at movement onset. For the TD-0 condition, target occlusion coincided with the auditory cue that signaled movement onset and for the TD-500, TD-1, 500 and TD-2, 500 conditions, the target was extinguished following the preview phase and the auditory cue sounded 500, 1,500 or 2,500 ms later. Kinematic variables including reaction time, movement time and peak velocity were measured as well as the constant error in the primary (mediolateral) and secondary (anteroposterior) movement directions and their associated variable error values.

As part of his analysis to determine the effect of the limb visible compared to the limb occluded mode of reaching, he employed a regression technique to examine the contributions of offline and online control processes across the different limb and visual conditions. He examined the proportion of variability (R^2) in the endpoint position marked by the position of the limb at peak acceleration, peak velocity and peak deceleration. He found that in limb occluded trials the spatial location of the limb at peak velocity and peak deceleration, which mark a later portion of the movement, was highly related to the movement endpoint. This suggests that the movement was highly dependent on central planning mechanisms working before the movement was initiated. The same result was not observed in the limb visible trials meaning the location of the limb at the aforementioned kinematic markers were not highly related to the endpoint of the movement suggesting that the movement was not largely pre-planned. Rather Heath suggested these findings demonstrate that the movement was being controlled online using feedback from vision of the limb to make corrections as the limb approached the target endpoint of the movement. Heath also suggested these findings demonstrate how vision of the limb during the movement results in an online and feedback-based method of reaching.

When evaluating the constant error, Heath found that movements made in the limb visible condition had longer movement times than those made in the limb-occluded condition. He found that reaching in limb visible trials was more accurate than reaching in limb-occluded trials. In the limb-occluded condition, he found there was no difference in the endpoint error as a function of visual condition. The endpoint error remained the same whether the participant had full vision of the target throughout the movement or had a delay of 2,500 milliseconds. In contrast, the limb visible trials were most accurate in the T-V condition compared to the other visual conditions, which did not differ from one another. Endpoint variability was also significantly less in the limb visible condition.

Since the presence or absence of visual information about the target regardless of delay did not influence the accuracy of the movement in the limb occluded reaching condition, Heath concluded that the movement was controlled off line based on central planning processes prior to the movement onset. He showed that only when the hand was visible during pointing was there evidence for a memory representation of target information. That is, vision of the hand enabled people to use the stored representation of target location to guide their movements.

Therefore, the stored target information may be more stable and accurate than previously thought and may not necessarily be as temporally sensitive as reported in previous experiments (Elliott et al., 1987; Westwood et al., 2001, 2003). Heath further attributes "decreased limb coordinate estimation", or lack of vision of the limb, as a reason why movement accuracy was not influenced by the visual target delay information.

One of the main goals of this study is to examine the effects of aging on moving to remembered targets. Given Heath's interesting findings, we wanted to conduct an experiment in which the stored target representation would be fully utilized without interference from processes attempting to map limb coordinates during the movement in an offline mode of reaching. So in this study we chose to use a condition (closed-loop) in which vision of the limb was available throughout the movement.

Movement Control and Aging

Many studies have examined the effects of natural aging on movement control and found an overall reduction in the speed of the movement profile compared to their young counterparts (Roy et al., 1993; Yan et al., 1998). Results have shown that movement times increase, peak velocities decrease, and the amount of time or proportion of the movement spent in deceleration increases. This latter finding has been the most prominent explanation for the general slowing of movements on the part of healthy aging individuals. In a study aimed at examining the kinematics of healthy older participants, Pratt, Chasteen, and Abrams (1994) decomposed reaching movements that healthy young and older participants made using a handle connected to a potentiometer to move a visible cursor to a specified region on a video monitor. They broke the mean movement time down into two submovement times, T1 and T2. T1 marked the initial ballistic portion of the movement while T2 marked the error-correcting portion. Results showed that the healthy older group had significantly longer overall movement times, which was attributed to the T2 portion of the movement time. The T1 portion did not differ between groups however the older group traveled much less distance in this primary submovement than did the young group. Consequently, the older group had much longer distances to be covered in the T2 secondary submovement. One reason for this longer movement distance and time in this T2 or deceleration phase could be that the older adults require more time to process the feedback information to make error corrections before completing the movement.

Aside from changes in kinematic profiles of movements of healthy older individuals, Chaput and Proteau (1996) have demonstrated that the ability to sufficiently use proprioceptive information in reaching movements is also affected by age. They found that when tested in a condition where only the target to be reached and not the limb was visible, so that proprioception was the only form of sensory feedback as to the location of the arm in space relative to the visible target, healthy older participants were less accurate than the healthy young participants.

Chaput and Proteau further expanded on their findings with a second experiment (1996) examining the ability to acquire visual and proprioceptive information to use in reaching movements when visual information was not given in subsequent trials. They provided two groups of healthy young and healthy older individuals with one of two acquisition reaching conditions; the proprioception and vision (PV) condition and a proprioception (P) condition. The PV condition required the participants to make a reaching movement to a target under normal lighting conditions so the participants could see their reaching hand for the duration of the movement. In the P condition, the lights of the experimental room were extinguished so that only the target was visible for the movement. For the group that performed the acquisition phase in the P condition, the healthy older participants were less accurate than the healthy young participants. Also, the healthy older participants did not improve over the 200 acquisition trials despite being given visual feedback about the limb's location relative to the target at the end of each trial. Since the older adults were less accurate only in the P condition, the authors concluded that the older adults were less accurate when reaching was based only on proprioception and they are less able to map the coordinates of a target location in body space using proprioception.

Effects of Age on Memory-Based Reaching

In the study by Chaput and Proteau, the effects of aging on reaching were examined in one condition (P) where the target, but not the limb, was visible throughout the movement, so the accuracy of the movement in reaching the target depended on the proprioceptive feedback from the unseen arm. Lemay and Proteau (2002) examined the effects of aging on movements to remembered targets where neither the target nor the limb was visible. Lemay and Proteau evaluated movements to remembered targets between a healthy older group and a healthy younger group using liquid-crystal goggles to create 4 different visual conditions: a delay of either 0, 100, 1,000, or 10,000 ms. Participants were given a preview phase of either 50 or 500 ms where they viewed the target before the goggles went to their opaque state. One of nine potential target locations was viewed on a computer screen and they moved a pointer placed at the bottom of the screen in a parallel direction.

The results of the experiment revealed significantly greater variable error but not constant error for the shorter presentation time. The constant error was significantly greater for the 1,000 and 10,000 ms delays, which did not differ from one another, compared to the 0 and 100 ms delay conditions, which also did not differ from one another. The variable error was also much greater for the 10,000 ms delay condition compared to any of the other visual conditions, which did not differ from one another. The most interesting finding was the absence of a group effect between the healthy older and healthy younger groups for either presentation time or delay time. Based on these findings, it would appear that the amount of time required to encode the target in its location is not affected by age. Also, the ability to effectively use the stored target information is not impaired by age either.

A study by Sarlegna (2006) supports the findings by Lemay and Proteau but also demonstrates how age can affect real time processing in movement control. They had older and younger participants make movements with a pointer to either a virtual central target or a virtual displaced target. At the beginning of each trial, the pointer illuminated for 2 seconds to provide visual information about the position of the reaching limb. After the pointer was extinguished, the central target was illuminated which means participants did not have vision of their reaching limb during movement execution but had vision of the limb before each trial. The experimenter indicated that a change in target location may occur which indicated the double-step trials. In this condition, a target would appear in a location lateral (either to the right or left) of the central target and an auditory cue would sound from the corresponding side of the participant who had to modify their movement as quickly as possible to accurately reach the displaced target. There were three visual conditions; one where the new target would remain constant until the end of the trial, another where the target it would be flashed for 50 ms, and a no-vision condition, where the central target would disappear and the auditory stimulus was the only indication of which lateral position the participant had to point to.

In the single-step trials, the participants were instructed to wait for an auditory cue to sound from a speaker on either their right or left side to initiate movement. The central target was displayed for 800 ms and once it was extinguished, the right or left speaker would signal participants to move in the corresponding direction. There were three visual conditions; one where there was no vision of the displaced target so participants were instructed to point to an imagined target located 15 cm to the right or left of the central target, another where, in addition to the auditory cue, the target was continuously displayed in the corresponding direction, and another where the target flashed for 50 ms in the direction corresponding to the auditory cue and then disappeared. The primary difference between the single and double-step conditions is that a movement perturbation occurred in the double-step whereas the terminal endpoint of the movement was constant in the single-step condition.

Analyses of the single-step condition revealed no effect of age on the movement accuracy in any of the visual conditions consistent with what Lemay and Proteau had found. That is, regardless whether the target was continually visible throughout the movement, whether it was flashed for 50 ms or whether it was visualized at a specific location, the movement error was not affected by age. Results differed from Lemay and Proteau's for the double-step movements, however, here there was an age effect in that the older participants were less accurate to the displaced targets, modified their movements later and were more variable than the healthy younger participants. This could indicate that changes in the movement trajectory are processed more quickly and effectively in younger individuals who appeared to be better able to correct their movements when they encountered a displaced target. It could also indicate that older adults are less adaptable when required to react to updated visual information in real time.

An interesting feature of many of these studies on reaching to remembered targets is the targets are typically encoded in an egocentric frame of reference. Lemay and Proteau (2003) conducted another study where they examined the effects aging had on movements to remembered targets encoded in an allocentric frame of reference. Participants in two groups, healthy young and healthy older adults, had to move a pointer from a fixed starting position towards one of four targets. One target was to be remembered while three were to remain visible. This ensured that the individual was encoding the target with respect to the other targets and with respect to themselves. To begin each trial, four white targets were presented on a black background on a computer screen for 1,000 ms. The targets were all the same size and were presented within an area of 2,500 mm^2 on the screen. The location of each of the four targets was random within the designated area and different for each trial. After the 1,000 ms presentation time, all four targets were extinguished. Following a 10,000 ms delay, three of the four targets reappeared in the same configurations they were presented in but in different colours and in a different location on the screen. Participants were asked to point to the location of the missing target and were then instructed to point to each of the coloured targets. The three targets were now presented in green, yellow and red. Therefore, the context in which participants are pointing to the remembered target is not relative to its original location on the screen, but relative to the other targets it was presented with. The movement time and constant error and variable error for both the direction and extent of the movement, were measured.

Analysis revealed an Age x Target x Recall Location interaction for both the direction and extent components of variable error where the older participants were significantly more variable than younger participants for the remembered targets but not the visible ones. There was also an interaction effect between groups and recall location for constant error for the direction component of the movement. Participants undershot remembered targets to a greater extent than visible targets when they were positioned on the right of the screen but not when the targets were presented on the left of the screen and these effects were much stronger in the healthy older group. This means they undershot the remembered target to a much greater extent than their younger counterparts. They also found that movement times to the remembered target were significantly greater for all participants but the older participants took longer to reach the remembered target than the young group.

The findings of this study are significantly different from the previous study Lemay and Proteau conducted with regards to the effects of aging on movements to remembered targets. Due to the difference in the nature of the aiming environment, in that participants were reaching in an allocentric rather than an egocentric frame of reference. Based on the results for the variable error, it appears that aging does affect the ability to maintain a stable representation of the stored target information when the target is coded in an allocentric frame of reference.

Effects of Amplitude and Position on Memory-Based Movement

As mentioned previously, it has been well established that movements with larger amplitudes have different kinematic profiles than movements with smaller amplitudes. However, do these findings still apply in the context of reaching to remembered targets?

A study by Lemay and Proteau (2001) investigated the reason for previous findings that reaching movements to remembered targets become less accurate with increasing movement amplitude (Adamovich, Berbinklit, Smetanin, Fookson and Poizner, 1994); an effect they termed the 'distance effect'. They used the same experimental set-up as their study mentioned previously (Lemay and Proteau, 2001) where healthy older and younger participants moved a pointer along the bottom of a screen to indicate one of nine potential target locations. Within each age group, there was an experimental and control group. In the control group, participants were instructed to reach to the remembered target location as accurately as possible and were given no temporal constraints to do so. In the experimental group, participants were instructed to complete the movement in a time between 2 and 5 seconds for the 4 targets closer to the home position and approximately 1 second for the 4 targets farthest away from the home position. The middle target was given a movement time range of between 2 and 5 seconds for one half of the trials and 1 second for the other half. In both conditions the targets were previewed for either 50 or 500 ms and liquid crystal goggles were used to occlude the reaching environment. The investigators only imposed two visual conditions; a no vision condition with a delay of 100 ms and another with a delay of 10,000 ms. An auditory cue was given to signal participants to initiate the reaching movement.

Analyses of the absolute constant error and the variable error of aiming revealed a significant distance effect for both variables for the control group where there was a larger aiming error for the targets that were farther away than for the closer targets. However, they found a reverse distance effect for both dependent variables for the experimental group where there was larger absolute constant and variable error for the nearer targets which required more time to reach (2 to 5 seconds) compared to the targets that were farther away (1 second to reach). The results led the authors to suggest that the distance effect is cause by the movement duration. The movement duration hypothesis suggests that a distance effect occurs in movements to remembered targets because movements to targets that are farther away take longer and allow the stored target information to decay over the course of the movement resulting in less accurate and more variable endpoints. It is also worth noting that they did not find any affect of age meaning the distance effect was not amplified by age.

However, whether or not the *position* of the target influences the constant or variable error is another question. The position of the target relative to the reaching hand influences the movement time so that movements to targets on the ipsilateral side of the body have shorter movements times than targets located on the contralateral side of the body (Roy, Kalbfleisch, and Silcher, 1999). The movement duration hypothesis suggests that it is not the amplitude of the movement that influences the terminal accuracy, but the duration of the movement itself. This would suggest that movements to the contralateral target positions would be less accurate than movements to the ipsilateral target locations.

Objectives and Hypotheses:

There are four main objectives we hope to accomplish with this experiment.

1a) The first objective is to confirm previous findings that healthy aging has an effect on the control of visually-guided reaching movements with respect to their kinematics. We hypothesize that in a condition of visually-guided reaching where both the limb and the target are visible, the healthy older group will have longer movement times, lower peak velocities and greater time spent in deceleration compared to the healthy younger group.

1b) Along with this, we want to evaluate whether the distance or position of the target location affects either the movement profile or accuracy. We hypothesize that there will be a distance effect for both groups where movements made to targets with larger amplitudes will have longer movement times, greater peak velocities and greater endpoint error and variability. However, based on the findings of Lemay and Proteau (2002) where they found no effects of age on movements to remembered targets, we do not expect to find an effect of age on the predicted distance effect.

2) The second objective we have is to confirm previous findings that memory-guided aiming movements differ from visually guided aiming movements, specifically in closed-loop reaching conditions. We hypothesize that the closed-loop reaching method will allow participants to fully utilize the stored target information and furthermore, that memory-guided movements will be significantly less accurate and more variable in the endpoint of the movement than movements made in the control condition where vision of the target and limb are available. Consequently, we hypothesize that memory-dependent movements made in conditions where a longer delay is imposed will be less accurate and have more endpoint variability than movements made in conditions where a shorter delay is imposed.

3) The third objective is to examine whether or not the normal aging process affects reaching movements to remembered targets. We expect various visual conditions to be optimal for showing a difference between the control and memory-guided movements

and hence for finding a difference between the young and older adults if one exists. We expect that the older adults will be less accurate, have more endpoint variability and have longer movement times in moving to remembered targets.

4) Our final objective is to examine whether or not experience with visually guided reaching movements affects the accuracy of memory-guided movements and if age is a factor in this. In this study participants pointed at the targets in two blocks of memory-guided trials separated by a set of control trials. In the memory-guided trials the targets were presented briefly and then disappeared prior to movement initiation. Participants then had to point to the remembered locations of the targets. In the control trials the target was visible throughout the pointing movement. We reasoned that in the first block of memory-guided trials, movements to the targets would be largely directed by the visual representation of the target locations. In the second block following the experience in the control trials at mapping the visual with the proprioceptive (felt position) information about target locations we expected to see a decrease in endpoint error and variability relative to that seen in the first block of memory-guided trials.

Based on the study by Chaput and Proteau, we expected this improvement in memory-guided reaching to be smaller for older adults. Recall they found their older adults to be much less able to map proprioception using vision when reaching to targets. Older adults in our study then may benefit much less from the experience with mapping vision and proprioception in the intervening control trials thus leading to a smaller improvement in reaching performance in the second block of memory-guided movements.

Methods

Participants

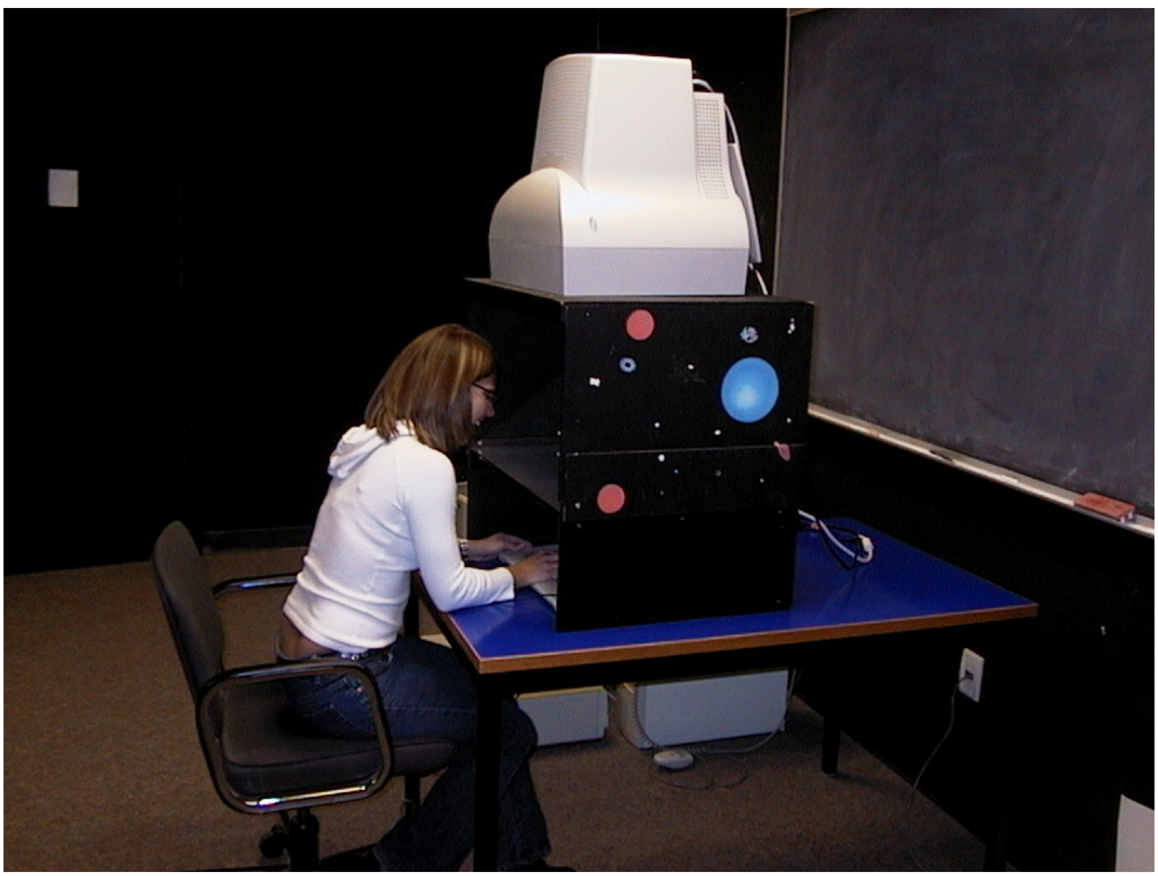
This study included two groups of healthy adults. The first group consisted of 10 healthy young adults, 5 male and 5 female, ranging in age from 18 to 38 years old with an average age of 22.7. These participants were recruited from the Psychology Participant Pool in the Psychology Department at the University of Waterloo. The second group consisted of 10 healthy older adults, 4 male and 6 female, ranging in age from 61 to 83 years old with an average age of 69.0. These participants were recruited from the Waterloo Research Aging Pool at the University of Waterloo.

The selection criteria for each of the participant groups were as follows: no history or signs of neurological impairment (such as stroke), no problems with auditory acuity or problems with visual acuity that could not be compensated for by corrective eyewear, no musculoskeletal problems in the upper extremities (such as arthritis) and they must be right handed. The selection criteria specific to each group were that they must be between the ages of 18 and 40 for the healthy young group and they must be between the ages of 60 and 80 for the healthy older group.

Apparatus and Testing Materials

The apparatus used to present the manual aiming task consisted of a wooden box (55 cm w x 60 cm d x 120 cm h) resting on a table. The box itself was divided into two separate compartments by a reflective mirror placed parallel to the top and bottom of the box. A square hole was cut into the top of the box and a computer monitor was placed there so that the screen image on the monitor was projected on to the reflective surface of the mirror. In the bottom compartment of the box below the mirror, a graphics tablet and mouse were placed so that the participant could make movements with the mouse without vision of their hand. Therefore, participants were seated in front of the box looking at the mirror in the upper compartment and controlling a mouse on a graphics tablet in the lower compartment.

Figure 1: Testing Apparatus



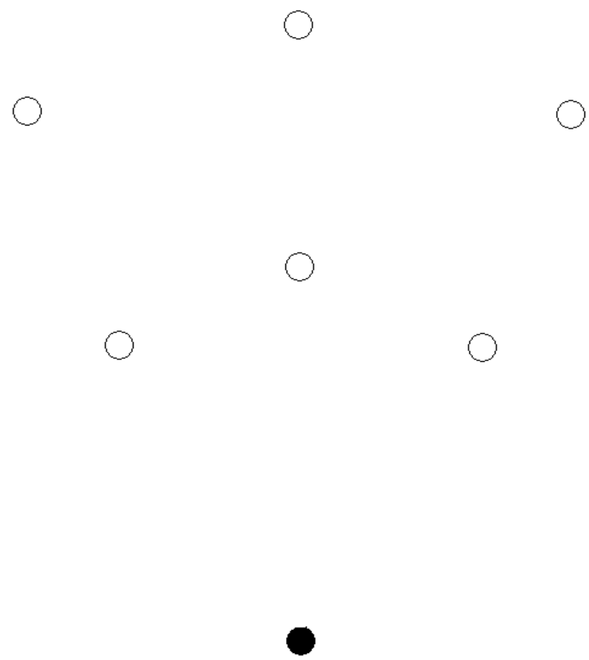
The movements made with the mouse were detected by a computerized SummaSketch III digitizing tablet sampling at 23 Hz. There was a one-to-one ratio of movement between the mouse and the cursor on the mirror. Therefore, the movements of the mouse on the graphics tablet were fully representative of the movement of the cursor on the screen.

Procedure

Each participant was tested individually in a small testing room where external noise was eliminated. The total testing time was approximately 60 minutes. All participants were given the opportunity for short breaks if they wished. All testing was conducted by a research assistant.

The aiming task consisted of a home position at the bottom of the screen and graphics tablet at the participant's midline. There were six target locations on the screen; two on the midline, two in ipsilateral space and two in contralateral space. The directions of the targets in ipsilateral and contralateral space were 30^{o} from the midline on either side respectively thus producing a semi-circle or arc with the target positions. Within these six target locations, there were two different amplitudes; 15 cm and 30 cm away from the home position respectively. Therefore, the placement of the six target locations produced two semi-circles, one inside the other.

Figure 2: Screen Display



The participant placed the mouse on the graphics tablet at the home position which corresponded with the home position for the cursor on the screen. Once the cursor was in place, the experimenter pressed a button which began the trail. In the control trials, in which the target remained on during the aiming movement, a target appeared in one of the six locations on the screen. Once the target had been presented for one full second, an auditory tone cued the participant to move the cursor to the target location. On the memory trials, the target disappeared before initiation of the aiming movement. In each trial the participant was instructed to reach as quickly to the target without sacrificing speed for accuracy.

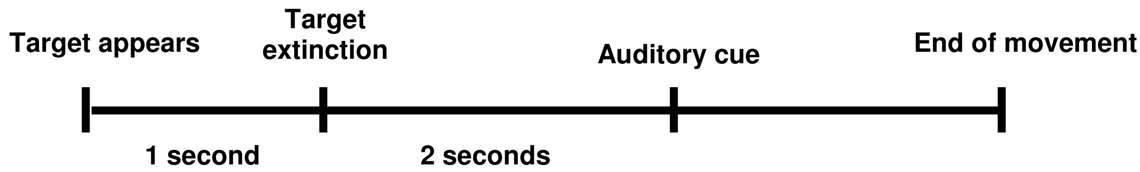
The aiming task was comprised of three aiming conditions; a control condition and two memory conditions. The control condition as noted above involved the target remaining visible to the participant throughout the duration of their movement to the target location. Therefore, they had full vision of the target in its position as they were making the aiming movement. There were six trials to each of the six target locations equaling 36 control trials in all.

The first memory condition was the immediate memory condition. It consisted of the auditory cue sounding immediately after the target location had been extinguished. Therefore, the participant's movement corresponded with the disappearance of the target. There were two blocks of immediate memory trials each containing three trials to all six target locations which meant there were 18 trials per block and 36 immediate trials overall.

Figure 3: Immediate Trial

The second memory condition was the delay memory condition. In this condition, the auditory cue sounded a full two seconds after the target had been extinguished. Therefore, the participant's movement did not begin until two seconds after the target had disappeared. There were also two blocks of delay memory trials each containing three trials to all six target locations. Therefore, there were 18 trials per block of delay trials and 36 delay trials overall. In all trials of all three visual conditions, there was no explicit knowledge of results (KR) given to the participants upon completion of the movement.

Figure 4: Delay Trial



Each condition was semi-randomized so that each target location would be presented once before the next set of trials began. Therefore, it eliminated the chances of repeated movements to target locations before movements to other locations had been made. The placement of each block of conditions was not randomized.

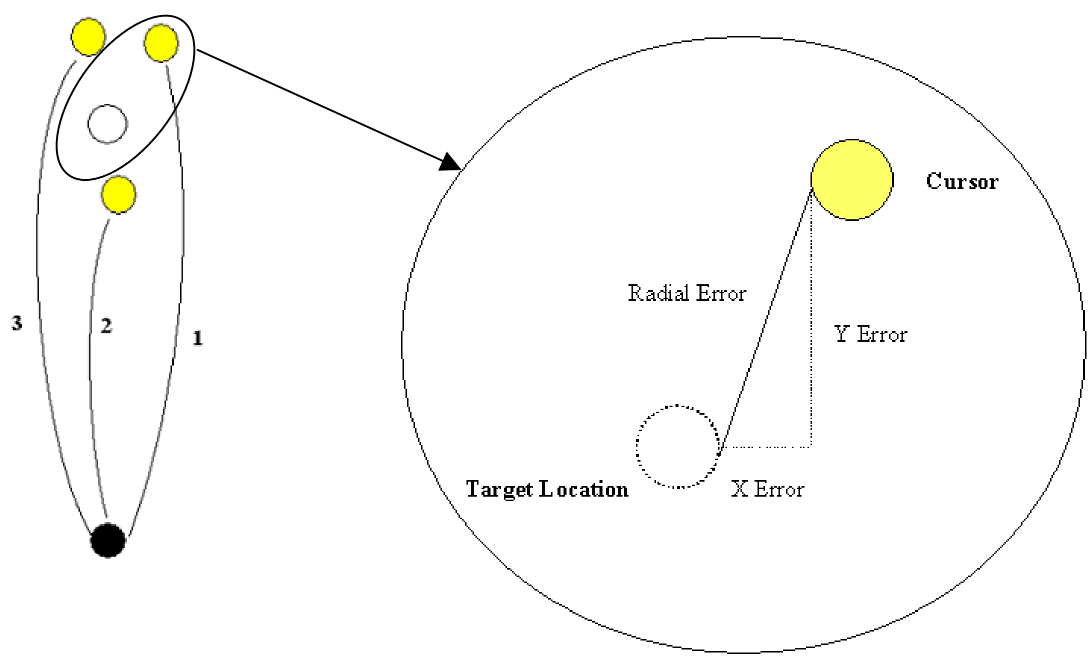
The order of the conditions was as follows: the first block of immediate and delay memory trials, the control trials, and then the second block of immediate and delay memory trials. Using this order we planned to examine the difference between the first and second block of memory trials to see if the experience in moving to the six targets in the control trials enhanced the memory for the target locations in the second blocks of memory trials.

Data Analysis

The movement and endpoint data were collected using the D-track program and analyzed using the KinAnalysis program. The data was analyzed using a dual-pass Butterworth filter with a low-pass cutoff frequency of 6 Hz to filter the two-dimensional data and a sampling rate of 23 Hz. Trials for which data were missing for technical reasons were excluded from further analysis. This equates to 3.61% of immediate recall trials, 3.87% of delay trials and 15.84% of control trials. All statistical calculations were performed using SAS version 9.1. Dependent variables included kinematic and accuracy data. The kinematic dependent variables were movement time, peak velocity, real time and percent time to peak velocity, real time and percent time after peak velocity. The accuracy-based dependent variables were endpoint error and variable error for the x, y and radial direction. As indicated in Figure 5, the endpoint error was measured as the distance between the edges of the cursor indicating the endpoint of the actual movement and the edges of the actual target location. The variable error was obtained by calculating the standard deviation of the endpoint error.

Three separate ANOVA analyses were performed using the means and standard deviations of the kinematic and endpoint accuracy. Statistical significance was based on an alpha value equal to 0.05. Only statistically significant or near significant results are reported.

Figure 5: Movement Endpoint Distribution and Error Measures



Results

Analysis 1: Performance of Control Condition

The first analysis was a 3 way ANOVA (Group X Amplitude X Direction) comparing the control trials between each group. Since the control condition had full vision of the target throughout the aiming movement, this analysis did not include the endpoint accuracy data and only examined the kinematic data.

Means

The analyses revealed only a main effect for movement amplitude for movement time, $F(1,18) = 48.43$, $p < .05$, peak velocity, $F(1,18) = 30.57$, $p < .05$, and time after peak velocity, $F(1,18) = 263.71$, $p < .05$. Movements to the farther targets exhibited longer movement times (long = 0.7478 sec; short = 0.5285 sec), had higher peak velocity (long = 309.985 mm/s; short = 192.442 mm/s) and had a longer time after peak velocity (long = 0.482 sec; short = 0.325 sec) than movements to the closer target locations. Tables 1 and 2 in Appendix C show means and standard deviations, below in brackets, for young and older groups in the control condition.

Standard Deviation

Analyses revealed no significant effects for variability. This means there was no significant deviation from the average kinematic variable values and suggests that the movement was performed with little deviation from the average every time it was executed.

Analysis 2a: Performance in Control and Memory Conditions

The second analysis was a 4 way ANOVA (Group X Condition X Amplitude X Direction) involving the means and standard deviations of the kinematic and endpoint data of the control and memory conditions. Since the control condition was not divided into blocks, both the immediate and delay memory conditions were collapsed across blocks for this analysis to isolate and compare the visual conditions without having to factor in the division of memory trials among the two separate blocks.

Means

There was an effect of amplitude for peak velocity $F(1,56) = 70.37$, $p < .05$, where movements made to farther targets had a much higher peak velocity (long = 288.86 mm/s; short = 180.31 mm/s) than movements to closer targets. There was a trend of amplitude for movement time $F(1,56) = 11.94$, p, .0745 and time after peak velocity $F(1,56) = 10.67$, p .0823. Movements to the farther targets tended to take longer (long = 0.848 sec; short = 0.651 sec) and had a greater time spent after peak velocity than movements to the nearer targets (long = 0.5787 sec; short = 0.446 sec). There was also a trend of condition with radial error $F(2,56) = 5.00$, p, .0761 where the control condition had significantly less radial error than both the immediate and the delay recall conditions (control = 2.759 mm; immediate = 4.552 mm; delay = 5.55 mm).

Standard Deviation

When examining the standard deviations of the kinematic data across all visual conditions, there was no statistically significant finding for the kinematic data. There was an effect of condition for amplitude error $F(2,56) = 23.83$, $p < .05$ where the control condition was significantly less variable than the immediate or the delay recall conditions (control = 1.994 mm; immediate = 3.158 mm; delay = 3.558 mm). Further analysis showed that the source of the effect was between the control condition and the memory conditions combined. There was also a trend towards condition for the radial error F (2,56) = 5.53, p, .0706 where the control condition was yet again less variable than the immediate or delay conditions (control = 1.521 mm; immediate = 2.44 mm; delay = 2.8 mm).

Analysis 2b: Performance of Control Compared to Blocks 1 and 2

Another analysis that was performed was to evaluate each block of memory conditions with each other as well as the control trials. There were 4 separate analyses performed: the first two were examining the means and standard deviations of the first blocks of both memory conditions and comparing them to the control condition.
The second two were comparing the means and standard deviations of the second blocks of both memory conditions to those of the control condition.

Means: Control vs. Block 1

When evaluating the means of block one of the immediate and delay to the control conditions, there was a trend towards condition on radial error F (2,26) = 6.36, p, .0572 where the control condition had a lower mean endpoint error than the first block of immediate and delay recall (control = 2.885 mm; immediate = 4.563 mm; delay = 5.746 mm). This trend was the result of the combined error values of the immediate and delay recall conditions against the control condition. Tables 3 to 6 in Appendix C present the means and standard deviations of young and older groups for the first block of memory conditions.

Means: Control vs. Block 2

When comparing the second block of each memory condition to the control condition, there were no statistically significant findings. Therefore, after using the control trials in between each block of memory trials, the second block trials were significantly more like the control trials than the first block trials. Tables 7 to 10 in Appendix C present the means and standard deviations for the young and older groups in the second block of memory conditions.

Standard Deviations: Control vs. Block 1

When looking at the standard deviations of the first block of the memory conditions and the control condition, there was an effect of condition on movement time $F(2,26) = 9.96$, $p < .05$ where the delay recall condition had less variability in movement time followed by the immediate condition and the control condition (delay = 0.098 sec, immediate = 0.11 sec; control = 0.162 sec). There was also an effect of condition on radial error $F(2, 26) = 36.8$, $p < .05$ where the control condition had the least amount of variable error followed by the immediate and then the delay recall condition (control = 1.5121 mm; immediate = 2.054 mm; delay = 2.62 mm).

Standard Deviations: Control vs. Block 2

When examining the second block of the memory conditions and the control condition, there were no statistically significant findings. Again, this condition effect for variable error mirrors that of the effect of endpoint error mentioned above. Therefore, when comparing each block of memory trials against the control trials, the second block is significantly more like the control trials than the first block.

Analysis 3: Performance Comparison of Memory Conditions

The third analysis was a 5 way ANOVA (Group X Condition X Block X Direction X Amplitude) involving the means and standard deviations of the kinematic and endpoint accuracy data for both memory conditions.

Means

Analyses of the kinematic means revealed an effect of amplitude on movement time $F(1,30) = 83.6$, $p < .05$, peak velocity $F(1,30) = 46.62$, $p < .05$, time to peak velocity $F(1,30) = 31.57$, $p < .05$, and time after peak velocity $F(1,30) = 30.9$, $p < .05$. Movements to the farther targets had greater movement time (long = 0.838 sec; short = 0.629 sec), higher peak velocity (long = 277.815 mm/s; short = 172.048 mm/s), longer time spent before (long = 0.273 sec; short = 0.207 sec), and after peak velocity (long = 0.5638 sec; short = 0.422 sec).

There was also a near effect of group for movement time $F(1,30) = 11.09$, p, .0796, where the older group exhibited lower movement time than their younger counterparts (older = 0.72 sec; young = 0.747 sec).

Analysis revealed no statistically significant results for mean endpoint accuracy.

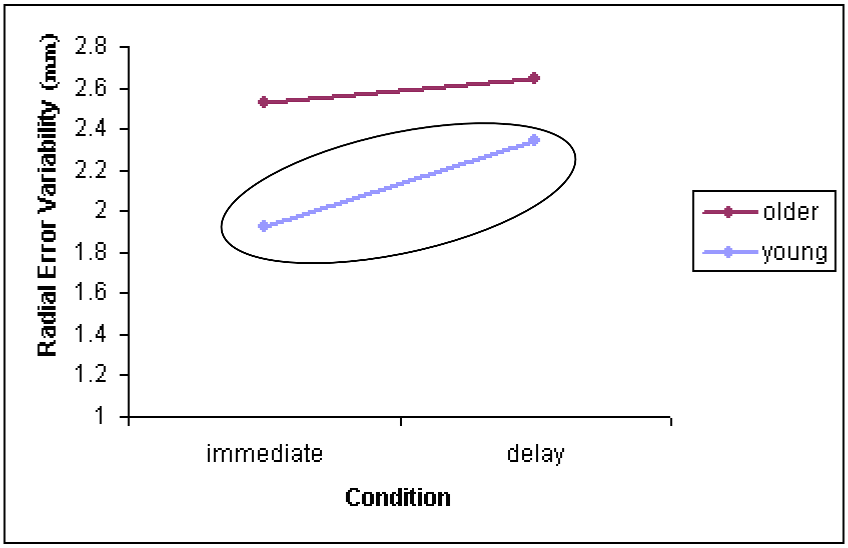
Standard Deviation

Analysis revealed no statistically significant results for the variability of kinematic measures. However, analyses of endpoint variability revealed an effect of condition on radial error, $F(1,29) = 40.36$, $p < .05$, where variability was significantly greater for the delay than the immediate condition (delay = 2.49 cm; immediate = 2.223 cm) as shown in Figure 6.

Figure 6: Condition Effect of Radial Error Variability

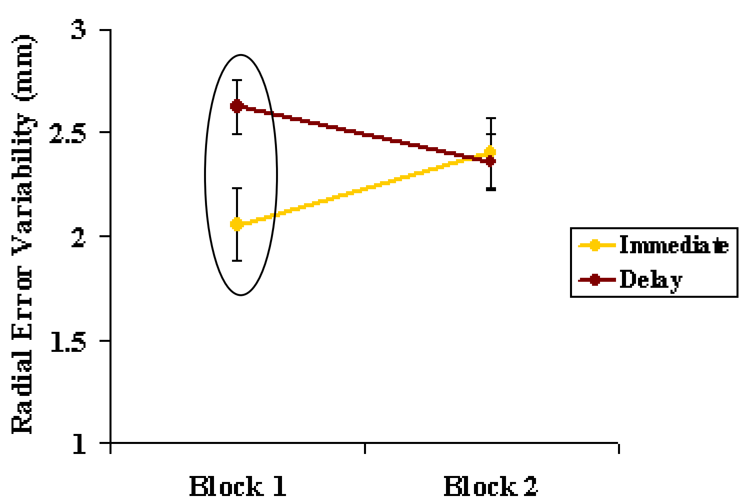
There was also a group by condition interaction for radial error $F(1,29) = 29.65$, $p < .05$. Further analysis showed that this interaction arose because the change in variable error from the immediate condition to the delay condition was significant for the young, $F(1,17) = 504.22$, $p < .05$, but not the older group. While both groups had less variability in the immediate than in the delay condition (see Figure 7), this increase was significant only for the young group. Note that both conditions for the younger group show less variability than either of the conditions for the healthy older group.

Figure 7: Group by Condition Effect of Radial Error Variability



There was also an interaction between block and condition F (1,29) = 26.4, $p < .05$. As shown in Figure 8, the variability in the delay condition decreased from the first to the second block (first = 2.622 cm; second = 2.358 cm). However, the variability in the immediate condition increased from the first block to the second block (first = 2.054 cm; second = 2.403 cm).

Figure 8: Effect of Block by Condition on Radial Error Variability



Upon further analysis, it was discovered that this interaction arose because the difference in the variable error between the immediate and delay recall conditions was significant only in the first block, $F(1,22) = 19.67$, $p < .05$.

Discussion

The objectives in this experiment were to confirm previous findings with regards to movement control and accuracy to targets after they have been visually occluded and the effect aging has on them. We also wanted to investigate whether experience with visually guided movements provides a basis for improvement when making memory-based movements to those same targets.

Movement Control in Full Vision Condition

The kinematic results from the control trials showed a distinct amplitude effect in movement time, peak velocity and time after peak velocity. This reflects the findings of several studies where movement times were longer, peak velocities higher, and time in deceleration was greater for movements with larger amplitudes (MacKenzie, Marteniuk, Dugas, and Liske, 1987; Roy, Weir, Desjardins-Denault, Winchester, 1999; Elliott and Madalena, 1986; Messier and Kalaska, 1999).

There were no effects of position found in the control trials suggesting that the position of the target relative to the reaching arm, i.e. whether the movement crosses the midline or not, did not influence the movement profile. This finding is inconsistent with that of Roy and colleagues (1999) where movements to contralateral hemispace yielded longer movement times and lower peak velocities compared to movements made in ipsilateral hemispace. The reason for the difference in the current findings is unclear. However, according to Carey and colleagues (1992) complex biomechanical demands of reaching are responsible for kinematic differences between the movements to contralateral and ipsilateral hemispace. It could be that the biomechanical demands were not significantly different in our present study to merit a significant difference in hemispatial kinematics.

Aging and Movement Control

Before we evaluated the effects of aging on the movements to remembered target locations, we first wanted to confirm the difference between the movements to visible targets of healthy older participants compared to healthy younger participants. When evaluating the control trials we found there was no age difference in the movement profile of the control conditions, which is where vision of the target was available throughout the movement. This is contrary to previous research (Roy et al., 1993; Yan et al., 1998), which illustrates that healthy older participants have longer movement times, lower peak velocities and longer time spent in deceleration. The reason for the incongruity in our findings to the results of previous studies is undetermined. One possibility for the lack of the typical longer movement time for older adults could be that there was no difference in the time spent in deceleration. As mentioned previously, longer time spent in deceleration is typically indicative of requiring more time to process feedback online, resulting in longer movement times. In our study, there was no difference in time spent in deceleration between age groups, which is one possible reason for the similarities in movement profiles between age groups.

Movements to Remembered Targets

One of the primary objectives was to reproduce the findings of previous studies of movements to remembered targets. Unlike many other memory-based reaching studies

(Elliott & Madalena, 1987; Flanders, Tillery, & Soechting, 1992; Westwood, Heath, & Roy, 2001, Heath, Westwood & Binsted, 2004), we did not find overall significant differences between the endpoint error measures in the different visual conditions. Generally speaking, there was no statistically significant main effect showing a difference between the full vision control condition and the two memory conditions, immediate and delayed recall. This suggests that the stored target information used in both the immediate and delay recall conditions, was of similar integrity as the condition where full vision of the reaching environment was available.

Not only was the endpoint accuracy similar between visual reaching conditions, but the movement profiles were similar across all conditions as well. The kinematic data shows that the movement time, peak velocity and time in deceleration, or time after peak velocity, were similar between all visual conditions. This suggests that the way the movement was carried out was not affected by visual restriction of the target. It is interesting to note that lack of vision of the target in the memory conditions, particularly the delay, did not influence the amount of time spent in deceleration. It is understood that the time after peak velocity typically indicates the portion of the movement when the on-line movement error corrections take place following the initial ballistic movement (Schmidt and Lee, 1999). Since the time in deceleration in this study did not differ between conditions, it suggests that the participants did not require any more time to correct their movements in the memory conditions than they did when they had full vision of the target. It could also suggest that the presence or absence of the target during the movement did not affect the error corrections themselves either. This would support

Heath's findings for his closed loop condition in which vision of the hand was present throughout the movement.

The similarities in the movement profile between control and memory conditions could be a result of two factors; the presence of the cursor to use as a reference point for visual feedback in order to make appropriate error-nullifying movements in any of the visual conditions, or the quality of the stored target representation was accurate enough that it allowed them to minimize the amount of time they had to spend correcting their initial ballistic movement. As explained further in this section, these factors may not necessarily be entirely independent of one another.

The overall endpoint error results confirm that they had no reason to make error corrections in any of the visual conditions, as their accuracy was no different from full vision to delay recall. The movement was treated the same regardless of whether the target was present during the movement or not. This is strong evidence supporting Elliott and Madalena's theory of a *"highly accurate"* visual representation of the target in its location in space and how it is associated with a high resolution of proprioceptive awareness.

Although the endpoint error results do support the existence of *"highly accurate"* stored target information, the variable error results do question the stability of this visual representation. The variable error showed the immediate memory condition was significantly less variable than the delay condition. The variable error speaks to the stability of the stored target information rather than its quality. The variance in the movement endpoints suggests that the stored target information is not consistently being accessed and utilized, or the strength of the representation varies over trials. The results suggest that it is not necessarily the ***quality*** of the stored target information but the ***stability*** that decays as a function of time.

We have interpreted this instability in endpoint variability as some problem in the strength of the memory representation of the target or in accessing or using this representation. It is possible though that this increased endpoint variability is due to greater variability in the control of movements to remembered targets which becomes more variable as a function of the delay. If this explanation were true, one would expect greater variability in the movement kinematics when moving to remembered targets compared to movements to the visible targets in the control condition. Further, within the movements to remembered targets one would expect greater kinematic variability in the delay than the immediate condition. Neither of these findings were observed in the data, suggesting that endpoint variability must be related to the strength of or access to the memory representation of target location.

This study evaluated two time dependent conditions: a zero-second delay, an immediate recall, where target extinction coincided with the cue for movement initiation, and a delayed recall, where movement initiation was cued 2 seconds after target extinction. Previous studies have found that time delays as little as 500 ms (Westwood, Heath, Roy, 2001) are enough to impair accuracy and variability in reaching movements to remembered targets. However, these studies were conducted without vision of the hand or cursor during the movement. Therefore, it is important to draw comparisons with a study that has looked at memory-dependent movements in a reaching environment where the limb was visible.

One such study was conducted by Heath and Westwood (2003). Similar to our study, vision of the hand (cursor) was available during movements to remembered targets using a mouse and computer screen. In contrast to our study, however, they varied the ratio of the movement of the cursor to the movement of the hand so that different conditions had different ratios, whereas in our study, this ratio was always 1:1 so that the distance moved by the mouse with the hand on the graphics tablet was the same as the distance moved by the cursor on the screen. Their reason for doing this was to decouple vision and proprioception, or the visual location of the target from the felt position and test whether memory-dependent reaching could be supported in a closed-loop reaching environment. This would allow them to examine the nature of the representation of the target location in memory in a closed-loop context.

Similar to our findings, their results showed increased variable error across their visual conditions as well. The variable error was least in the full vision condition; it then increased for their 0-second delay condition. It increased further for their 2-second delay condition where it plateaued for the 5-seocnd delay condition. These results reflect the findings of this study and further demonstrate that a delay period can influence the stability of the stored target information even when a feedback-based method of reaching is utilized.

However, unlike our findings, they showed that the error in returning to remembered target locations increased over their delay periods (0, 2 and 5 second delays) suggesting that visual information alone was not sufficient to sustain a representation of target location. Their findings in comparison to ours suggest that the quality of the representation of target location is dependent on this representation being based on both vision and proprioception.

The stability of this representation as reflected in the variability of the movements to remembered targets, does not seem as dependent on the coupling of visual and proprioceptive information. That is, regardless of whether there was this coupling, as was the case in our study, or not, as was the case in their study, the movement to remembered targets were more variable and this variability increased with the delay. It is possible though that the stability of the representation may be greater when there is coupling between vision and proprioception. Testing this hypothesis would require comparing the conditions in our study in which there is a coupling to those in the Heath and Westwood study where vision and proprioception are decoupled.

Amplitude and Directional Effects in Memory-Based Reaching

Previous studies have typically shown effects of movement amplitude when making either vision-dependent or memory-dependent movements to targets (Elliott & Madalena, 1987; Lemay and Proteau, 2001). Amplitude has been shown to affect movement kinematics, where movements over longer amplitudes yield greater movement times, as well as endpoint accuracy and variability, where larger movements yield greater movement error and variability. In the context of movements to remembered targets, Lemay and Proteau (2001) noted that both endpoint error and variability were greater to remembered targets associated with longer movement amplitudes and referred to this as the “distance effect” and related it to movement duration. That is, movements with longer amplitudes take longer to make resulting in more elapsed time before reaching the target and therefore, a longer time over which the stored target information can decay. Our study failed to replicate these effects for accuracy, as there was no effect of movement amplitude on endpoint accuracy. Unlike Lemay and Proteau, endpoint accuracy did not decrease as a function of movement amplitude. This lack of an effect may have been due to differences in the mode of movement control between the two studies. Lemay and Proteau used open-loop movements in which there was no vision of the hand during movements to the targets while we used closed-loop movements. Heath (2005) observed that vision of the hand enabled the development of a high quality representation of target location that was not evident when vision of the hand was not available. Such a high quality representation was evident in our study in that endpoint accuracy as well as the movement profiles for movements to the remembered targets was comparable to when the targets were visible throughout the movement. It is possible that the representation of the target was of such a high quality that it did not allow for an effect of movement amplitude on endpoint accuracy.

There were also no effects of position found for the memory conditions in that the position of the target relative to the reaching arm did not influence the movement time, or the endpoint accuracy or variability of the movement. Given the similarity between the control and the memory conditions in terms of accuracy and movement profile, it implies that there would be no effect of position in the memory condition considering no such effect was evident in the control condition. It may be that in both control and memory conditions, the biomechanical aspect of the movements into contralateral space may not have been any more complicated than movements to targets in the midline or in ipsilateral space to affect endpoint accuracy, variability, or kinematic measures such as movement time or peak velocity (Carey et al., 1992).

Effects of Experience in Memory-Dependent Reaching

In this study we also asked the question of whether a stored target representation could be enhanced by experience with pointing at targets that remain visible throughout the movement. To test this, we compared two blocks of memory-dependent reaching, each separated by a full block of pointing at visible targets (control condition). An improvement in endpoint accuracy or variability between blocks would indicate that performing visually guided movements to target locations with similar parameters prior to making memory-dependent movements, the motor system is somehow integrating information acquired in the target visible, or control, condition, and using it in the memory-dependent condition. Initially, our findings showed an improvement, or decrease, in the variable error in the delay recall condition from the first block of trials to the second, which is seen in a Block by Condition interaction effect. However, upon further analysis it was found that it was not the change in variability that was statistically significant, but the difference in the variable error between the immediate and delay recall of the first block that was the source of the interaction effect.

However, when each block of memory conditions was compared separately to the control condition, there were significant findings in the first block but not the second, indicating that experience in the control trials was helpful in improving the performance from blocks one to two. In block one, there was greater combined radial endpoint error in the immediate and delay recall conditions compared to the control conditions. This trend was also evident in the radial variable error of each of the conditions in the first block. Since both the endpoint and variable error were significantly different from the first block of memory conditions to the control condition, it suggests that the stored target information was not nearly as effective in making an accurate and stable movement to the appropriate location. However, the same analysis comparing the second block of each memory condition to the control condition yielded no significant findings at all. In block 1, prior to the experience in the control trials, endpoint error and variability were significantly greater following a 2 second delay compared to pointing to the remembered targets immediately after they disappeared. In block 2, however, performance in these conditions was comparable and pointing following a delay no longer resulted in greater endpoint error or variability.

These findings suggest that the second block of memory trials were more similar to the control trials than the first block. Therefore, it is possible that pointing to remembered targets is enhanced by experience of pointing at the same targets when they remain visible throughout the movement. This experience may enhance pointing to the remembered targets through integrating vision and proprioception. In block one, the movement to the remembered target is solely based solely on vision of the cursor to the remembered location and there is no reliable proprioceptive mapping that takes place. The control condition offers an opportunity to couple proprioception with vision such that in block two of the memory trials, participants have two reliable sources of information for pointing to the remembered targets at this point, thus enhancing their performance. In the Block 1 comparison with the control trials, the endpoint accuracy was not quite statistically significant which shows the experience of pointing to the visible targets appears to affect the endpoint variability more than the accuracy. It appears then that it is the stability of the representation of target location that is affected more by this experience, a finding which is further supported in the Condition by Block effect where the stability of the representation was only significantly different in between the immediate and control conditions in Block 1 only.

Neural Correlates of Memory-Dependent Movements

Previous research has suggested there are separate neural mechanisms for movements performed in open versus closed-loop reaching conditions. Milner and Goodale (1992) have identified two visual streams that process visual information once it passes the primary visual cortex; the dorsal and ventral visual streams. The dorsal visual stream, which reaches from the primary visual cortex to the posterior parietal cortex, is responsible for the egocentric localization of objects and for the online control of visually-guided movements. Meanwhile, the ventral visual stream, which runs from the visual cortex to the inferotemporal lobe is responsible for the perception of object attributes and some argue for the offline control of movements. The dorsal stream is typically the visual pathway implicated with the online control of action, however, it has been suggested that the ventral stream may be well-suited to maintaining a temporally stable, although less accurate, representation of the reaching environment in terms of movements to remembered targets (Heath, Westwood and Binsted, 2004). Although the ventral stream has been implicated in pointing to remembered targets, particularly when a movement delay has been imposed, this has typically been exclusive to experimental procedures that do not provide vision of the limb during the movement. In our study, it is likely that the dorsal stream was active in all reaching conditions since the participant had vision of the cursor at all times and likely used it in online movement control. It is also possible that the ventral stream still became active in the delay condition, as it is believed to be, but worked simultaneously with the dorsal stream since there was an online, visual cue in the form of the cursor. Since there was no difference in movement profile or accuracy between any of the conditions, it could imply that the dorsal stream was active in the control and immediate conditions, but it is also possible that both streams were active in the delay condition.

Effects of Age on Online, Memory-Dependent Reaching

Another issue addressed in this study is the effect normal aging has on feedback-based, memory-dependent aiming movements. In our study, there was no age difference revealed when looking at endpoint accuracy. However, the endpoint variability was greater for the older adults. In Lemay and Proteau's study, they found no effect of age on the accuracy or variability of movements to remembered targets. This discrepancy may have been due to differences in the mode of controlling the hand movement to the target. The one paramount difference between these two studies is the absence of vision of the hand/cursor during the movement. Vision of the hand was restricted in the Lemay and Proteau study, while vision of the hand/cursor was available in our study.

In looking at the effect of age on endpoint variability as a function of the delay condition, it appears that the effect is smaller when a delay is introduced prior to movement onset. This arises from the fact that endpoint variability increases with a delay for the young participants, and does not for the older participants. It is possible that no effect of delay is seen for the older group because they have reached a ceiling effect for the variability in their movement, even in the immediate condition, in which case imposing a movement delay would not significantly change that ceiling effect reached for variability.

This suggests that the older adults have a less stable representation of target location as reflected in their greater endpoint variability. It would appear that the stability of this representation is weak from the moment the target information disappears and does not become progressively weaker over a 2 second delay.

Interestingly, this greater endpoint variability for the older adults does not seem to be due to an inherently greater variability in moving to targets in space since the older adults do not exhibit greater endpoint variability when pointing at the same targets when they are visible throughout the movement. Rather, this increased variability must be unique to the task of pointing to remembered targets and likely reflects the stability of the representation of target location. The quality of the representation must be comparable to that of the younger adults since the older group does not differ from the young in endpoint accuracy.

When the stability of the representation of target location is reduced in the older adults, the control of the aiming movements is comparable to that for the young adults in that there are no group differences in movement time, peak velocity or the timing of peak velocity. Moreover the control of movements to these remembered targets is comparable to that for the movements pointing at the same targets when they are visible throughout the movement. This finding speaks to the high quality of the representation of the target location information for both age groups in the memory-dependent conditions.

Effects of Age on Experience with Visually-Guided Movements

As mentioned previously, the experience with visually-guided movements in the control condition influenced performance in the memory dependent condition. The first block of memory trials prior to the experience of pointing to the visible targets were quite different from the control trials, lower endpoint accuracy and greater endpoint variability, while the second block of memory trials following this experience were quite comparable to the control trials in accuracy and variability. Further, looking specifically at the memory trials, the stability of the representation of target location was lower in the delay than in the immediate recall condition in the first block of memory trials prior to the visuomotor experience in the control trials. This difference disappeared in the second block of trials after this experience suggesting an enhanced stability of the representation that was less affected by the length of the recall delay. This experience was thought to provide the opportunity to integrate vision and proprioception and so afford two reliable sources of information for pointing to the remembered target locations in block two. This effect of experience was independent of age suggesting that the older adults benefited from this experience as much as the young adults. This is unexpected given the increased reliance on visual feedback of older compared to younger adults reported in other studies (Chaput and Proteau, 1996; Heath et al., 1999). Given these findings one might expect that the older adults would have benefited less from this experience. Possibly the overall increased endpoint variability for the older adults when pointing to the remembered targets reflects a greater reliance on the visual component of the representation of target location or a reduced ability to consistently integrate the visual and the proprioceptive components of the representation when pointing.

Limitations

One significant limitation in this study is that it was not performed in a typical lights on/lights off reaching environment. The participant was seated at a chair looking into a black wooden box to see the reflection of the screen on the mirror with the lights on in the room. It is possible that external environmental cues, no matter how small, could have influenced the use of the feedback thus influencing the movement profiles or the movement trajectories.

If external environmental cues were present and did assist the participants in their movements, it is possible that they were not making reaching movements in an egocentric frame of reference but rather in an allocentric frame of reference. Lemay and Proteau have found that age does affect movements to remembered targets when they are encoded in an allocentric frame of reference.

Even if participants were reaching in a viewer-centered frame of reference, the presence of external environmental cues could still have influenced their movement accuracy or variability. A study by Admirall, Keijsers and Gielen (2003) examining the interaction between gaze and pointing to remembered targets, found that when participants were provided with vision of the reaching finger along with vision of a well-defined reaching environment, they were more accurate and less variable than when reaching in a dark environment with visual feedback from the pointing finger.

Another limitation may have been the sampling rate of the mouse movement, which was 23 Hz. Since many of the movements occurred in 1 second or less, there would only be 23 sampling points or less (depending on the movement's duration) taken during each movement. This sampling rate is a factor of 10 times less than many optoelectric systems such as Optotrak, which are at least 200 Hz. This sampling rate may have obscured differences in movement kinematics between the young and old and may explain why we did not find age differences in movement control. Indeed many of the studies of aging and movement control which have found large age differences have used movement analysis systems with sampling rates in the range of 200 Hz.

A final limitation may have been the nature of the pointing task used in this study. The task we used is a virtual pointing task in which the person does not see their hand but rather a virtual image of the hand in the form of the cursor. This task requires a sensorimotor transformation not involved in typical pointing tasks in which the finger/hand and the pointing surface can be seen directly. This transformation may have served to reduce the effects of age on performance.

Future Directions

We have compared the differences between the current study and others where memory-based movements have been visually supported to studies that provide a feedforward context of movement by restricting vision of the hand. The next step in this line of research has to be to directly compare the two types of paradigms in a single study. Since this type of study has been done by Carlton (1981) and more recently by

Heath (2005) where they directly compared an open-loop and closed-loop reaching paradigm, we would include the effect of age as an influencing factor.

It would also be interesting to use the analysis methods from Heath's study where he used a regression analysis to examine the proportion of variability in the movement endpoint in terms of the spatial location of the limb during the early (peak acceleration), middle (peak velocity), and later (peak deceleration) stages of the reaching movement. This is a form of kinematic analyses that allows you to see how the movement trajectory at various stages relates to the final endpoint, as well as see when corrective changes are made. A study examining the effects of aging on memory-guided reaching could examine the possible differences in when online movements occur relative to the final endpoint. This analysis technique would also be useful when examining the control trials in comparison to each of the blocked memory trials to distinguish the difference in how the movement is controlled in block two (after exposure to the control condition) and how that might differ from movement control in block one.

Another area of this study which may require further investigation, is the data obtained from the practice trials done at the beginning of the study protocol with each participant. Although the data from the practice trials was not recorded in this study, it may be that there is a significant difference between conditions or age groups that were noticeable within the first three trials.

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Appendices

Appendix A

Waterloo Research in Aging Pool (WRAP):

Participant Screening Questionnaire

WRAP
Participant Information Booklet

Participant Name:

____

Recruited from which Source?

____

Date Contacted:

____

Questionnaire Completed By:

____

Data Entered (Date):

____

Participant Identification Code:

General Information

Name:

Address:

Telephone:

Email:

Gender:

D.O.B.:

First Language (if not English, how old were you when you learned English?)

Total Education (in years):

Handedness:

If UW staff/faculty member, please indicate which department you work/worked in:

MEDICAL INFORMATION

1. *Please describe your general health.*

2. *Have you ever had any neurological problems (ie. strokes, seizures)?*

Yes No

If yes, please describe:

3. *Have you ever been unconscious for any length of time (ie. head injury, black-outs)?*

Yes No

If yes, please describe:

4. *Have you ever been diagnosed with any medical conditions or illnesses?*

Yes No

If yes, please describe:

5. *Have you ever had any surgeries?*

Yes No

If yes, please describe:

6. Do you drink alcohol?

Yes No

If yes: How many times per week/month?
How many drinks would you consume on the average occasion?
Preference: Beer Wine Liquor
Has it ever been a problem for you?
If yes: Did you receive treatment?

If no, did you ever drink? Yes No
How many times per week/month?
How many drinks would you consume on the average occasion?
Preference: Beer Wine Liquor
Has it ever been a problem for you?
If yes: Did you receive treatment?

7. Do you, or have you used recreational drugs including marijuana?

Yes No

If yes: Are you currently or was it in the past?
How often per week or per month?
Which drug or drugs?
How long have you been/were you using this drug for?
Did you ever receive treatment for it?

8. Have you ever been treated for anxiety, depression, or any other psychological problem?

Yes No

If yes: What were you treated for?
When did you begin receiving treatment?
How long did the treatment last?
What type of treatment did you receive?
Were you ever prescribed any medication?
What were you prescribed to take?
How long did you take that medication for?
Were you ever hospitalized?

9. Are you currently taking any medications?

Yes No

Drug	Dosage	Reason
1.		
2.		
3.		
4.		
5.		

10. Is your current weight over 200 lbs?

Yes No

What is your height? _________

11. Do you wear glasses or contact lenses?

Yes No

If yes: For reading or distance?

12. Do you have any difficulty with your hearing?

Yes No

If yes: Do you wear a hearing aid?

13. Have you ever had a stroke or a T.I.A? (Transient Ischemic Attack)?

Yes No

14. Have you been seen by a neurologist or a neurosurgeon?

Yes No

If yes: Was this for a back or neck problem?
If yes: Was this for a tension headache?

15. *Have you had cancer other than skin cancer diagnosed within the last three years?*

Yes No

16. *Do you have shortness of breath when sitting?*

Yes No

17. *Do you use home oxygen?*

Yes No

18. *Do you have difficulty understanding conversations because of your hearing even if you wear a hearing aid?*

Yes No

19. *Do you have trouble with your vision that prevents you from reading ordinary print even if you have glasses on?*

Yes No

20. *Have you had heart surgery?*

Yes No

21. *Have you ever been resuscitated?*

Yes No

22. *Do you have diabetes that requires insulin to control?*

Yes No

23. *Do you have hypertension that is not well controlled?*

Yes No

24. *Have you had a head injury with loss of consciousness greater than five minutes?*

Yes No

25. *Have you ever been unconscious for more than one hour other than during surgery?*

Yes No

26. Have you ever required overnight hospitalization because of a head injury?

Yes No

27. Have you had encephalitis or meningitis?

Yes No

28. Have you ever had a heart attack?

Yes No

If yes: Did you have any change in your memory, ability to talk or solve problems 24 hours after your heart attack?

29. Are you currently taking medications for mental or emotional problems?

Yes No

30. Have you been hospitalized for mental or emotional problems in the past five years?

Yes No

31. Have you ever had seizures?

Yes No

32. Do you have Parkinson's disease?

Yes No

33. Have you ever had brain surgery?

Yes No

34. Have you ever undergone surgery to clear arteries to the brain?

Yes No

35. Have you ever had any illness that caused a permanent decrease in memory or other mental functions?

Yes No

36. Have you ever received electroshock therapy?

Yes No

37. Have you ever been diagnosed as learning disabled?

Yes No

38. Were you placed in special classes in school because of learning problems?

Yes No

39. Have you ever been diagnosed as having a brain tumour?

Yes No

40. Do you have difficulty using your hands?

Yes No

41. Have you ever had major surgery with anaesthesia?

Yes No

If yes: Did you have any change in your memory, ability to talk or solve problems one week after surgery?

42. Do you have multiple sclerosis, cerebral palsy, or Huntington's disease?

Yes No

43. Are you receiving kidney dialysis?

Yes No

44. Do you have liver disease?

Yes No

45. Do you have lupus?

Yes No

Request for Participants Summary

New Request? _____ Request for Additional Participants? _____ - project #________

Name of Project: Contact email: ______________________________

____

Principal Investigator (please indicate if you are a student):
____

Collaborators (if you are a student, please indicate your supervisor):
____

Number of participants required: ______________________________

Anticipated duration of study (minutes): ______________________________

Inclusion criteria:
____

Exclusion criteria:
____

ORE Approval number: ______________________________

Type of study (ie. memory, cognitive, etc.): ______________________________

Testing requirements (time, number of sessions, type of testing, location of testing, etc.):
____

For WRAP - Project completed? (Date): ___________________________

I agree to hold any personal information about potential participants in the strictest confidence. I agree to contact these participants for the purposes of the study described above, and I agree to notify the WRAP Coordinator as soon as I no longer require these participants for the purposes of this study. I will not contact potential participants that I know personally, or whose names are familiar to me – instead, I will notify the WRAP Coordinator of this conflict of interest immediately, and additional names will be provided to me in order to replace the ones that I recognize. I agree to provide the WRAP Coordinator with a one-page summary of this study upon request, to facilitate publication of the WRAP Participant Newsletter. I HAVE READ AND AGREE TO ABIDE BY THE POLICIES AND PROCEDURES ASSOCIATED WITH WRAP.

Signed: _________________________________ *Date:* ________________________

Appendix B

Information, Consent, and Feedback Forms

INFORMATION LETTER

Title of Project: **EFFECTS OF AGE AND EXPERIENCE ON MEMORY-GUIDED MOVEMENTS**

Investigator: Amanda Skakum, BSc (Kin)
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Thesis Supervisor: Eric Roy PhD., C.Psych.
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This study is being conducted to investigate how hand movements to various targets are controlled and remembered, and the consequences that aging has on these processes. Relatively little is known about how aging affects memory for and control of movements to targets in space.

As a participant in this study, you will be asked to move a cursor on a computer monitor using a mouse. By moving the mouse you will hold in your hand you will move the cursor to a target shown on the computer monitor. After you hear an auditory cue, you are to initiate movement and move the cursor on the screen to the target via the mouse.

Firstly, you will perform a series of practice rounds in order to familiarize yourself with the experimental procedures. In the first half of practice you will perform control conditions in which the target remains on the screen throughout the movement. You will begin by positioning the mouse into the home position. A target will appear on the screen, and will remain visible throughout the whole attempt. You will hear an auditory cue, and once that sounds, you will try to move the cursor to the target location on the screen using the mouse as fast, but as accurately, as possible. Once you feel you have hit the target spot, you will click the mouse button to indicate movement termination. The next half of the practice round will consist of 5 target memory tasks, where the target disappears before the auditory cue is sounded. There are two types of memory conditions. The first, called the "immediate memory" conditions, employs the same procedure as the control conditions, with the exception that once the auditory cue sounds, the target on the screen will disappear. You will be asked to bring the cursor to where you remember the target was located prior to the auditory cue. The second memory condition is called the "delayed memory" condition in which the target will disappear before the auditory cue is sounded. Here you must wait until the auditory cue sounds before you move. You must again move to where you remember the target was located on the screen.

After the practice rounds, you will perform in the same three movement conditions in the following order: immediate memory condition, delayed memory condition and control condition. In each condition you will move to six different targets. There will be 18 tries in each the immediate and delayed memory conditions, and 36 tries in the control condition, making a total of 108 tries. Your movements on these assessments will be recorded on the computer and analyzed in terms of accuracy and movement kinematics, such as movement time. Your participation is expected to last around 45 minutes.

You may not benefit personally from your participation in this study. However, the information obtained from this research may lead to furthering knowledge in the psychomotor behaviour field within Kinesiology. As well, your participation may aid in future studies that may be useful for research with people that have various disorders and disabilities. Since finger pointing task are suggested to be representative of visual motor control (Roy, Weir, Winchester & Desjardins-Denault, 1999), the tasks in this study are appropriate to extrapolate to studies of other general types of movements in the same field of study. You may also learn about your own motor capabilities within the visual aiming domain. Lastly, you will have first hand experience in a neuropsychology laboratory setting.

We want you to be aware of the possible risks associated with participation in this research. There are no known risks for healthy participants. However, some participants may become anxious when performing the tasks, due to the hurried nature of some of the tasks. As well, because there are multiple trials that will be performed, some participants may feel tired. If this occurs, a break can be requested.

All information collected from participants in this study will be collectively combined. Thus, your name will not appear in any report, publication or presentation resulting from this study. The data, with identifying information removed, will be retained indefinitely and will be securely stored in a locked room in Burt Matthews Hall or kept with the investigator.

If you have any questions about participation in this study, please feel free to ask the researchers. If you have additional questions at a later date, please contact Dr. Eric Roy at the University of Waterloo (519-888-4567, ext. 3536) on any weekday between 8:30 A.M. and 4:30 P.M. You are under no obligation to participant and may withdraw from the study at any time by advising the researcher of this decision. In no way will this impact your relationship with the university, or the researchers.

I would like to assure you that this study has been reviewed and received ethics clearance through the Office of Research Ethics. However, the final decision about participation is yours. If you have any comments or concerns resulting from your participation in this study, you may contact Susan Sykes, Director of the Office of Research Ethics at (519) 888-4567 ext. 36005, or by email at ssykes@uwaterloo.ca.

CONSENT OF PARTICIPANT

I have read the information presented in the information letter about a study being conducted by Amanda Skakum, Karen Lau, and Dr. Eric Roy of the Department of Kinesiology at the University of Waterloo. I have had the opportunity to ask any questions related to this study, to receive satisfactory answers to my questions, and any additional details I wanted. I am aware that I may withdraw from the study without penalty at any time by advising the researchers of this decision.

This project has been reviewed by, and received ethics clearance through, the Office of Research Ethics at the University of Waterloo. I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact the Susan Sykes, Director, Office of Research Ethics at (519) 888-4567 ext. 6005.

With full knowledge of all foregoing, I agree, of my own free will, to participate in this study.

____

Print Name

____

Signature of Participant

Dated at Waterloo, Ontario

Witnessed

FEEDBACK LETTER

Title of Project: **EFFECTS OF AGE AND EXPERIENCE ON MEMORY-GUIDED MOVEMENTS**

Investigator: Amanda Skakum, BSc (Kin)
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I would like to thank you for your participation in this study. Aging is a combination of inevitable processes that involves every aspect of the human body. A method of investigating the effects of aging is to have both young and elderly adults perform movements that require precision and mental representation of a goal (Roy, Weir, Winchester & Desjardins-Denault, 1999). A suggested method to execute these movements is to carry out a pointing and reaching task (a movement which requires some precision), in situations that call for participants to reach to targets both in full vision and memory conditions. These categories of action are termed, "visually guided" and "memory dependent" (also known as, "goal reproducing") movements, respectively. As a reminder, the objective of the proposed study, then, is to determine how normal, healthy individuals of 2 different age groups differ in performance of precise pointing movements.

This study required participants of different ages in order to compare various characteristics of movement, including pointing accuracy, as measured by radial error, reaction time (the time it takes to initiate movement), movement time (the time it takes to complete a movement), as well as other measurements, such as velocity, acceleration and deceleration. The movement distance to the targets and the spatial position of the targets varied in order to examine the effects of these variables on the accuracy of your movement to the target location. For example, it is expected that targets further from the home position will be less accurate (larger radial error), although there should not be a significant difference between young and older healthy people.

The information obtained from this research may lead to furthering knowledge in the psychomotor behaviour field within Kinesiology. Data collected may also lead to useful knowledge regarding how aging affects the motor and cognitive system in terms of fine motor control and memory. Lastly, participation may aid in further studies that may establish normative data useful for research with special populations.

Please remember that any data pertaining to you as an individual participant will be kept confidential. If you are interested in receiving more information regarding the results of this study, or if you have any questions or concerns, please feel free to contact my project supervisor, Dr. Eric Roy, at the University of Waterloo (519-888-4567, ext. 33536) on any weekday between 8:30 A.M. and 4:30 P.M. If you would like a summary of the results, please let me know now by providing me with your resident address, or email address. When the study is completed, Dr. Roy and I will send the information to you. The expected date of study completion is by August 1, 2006.

As with all University of Waterloo projects involving human participants, this project was reviewed by, and received ethics clearance through, the Office of Research Ethics at the University of Waterloo. Should you have any comments or concerns resulting from your participation in this study, please contact Dr. Susan Sykes in the Office of Research Ethics at 519-888-4567, Ext., 6005.

Appendix C

Means Tables

Table 1: Control Conditions - Young

Dependent Variable	Contralateral		Midline		Ipsilateral	
	Near	**Far**	**Near**	**Far**	**Near**	**Far**
Movement Time (s)	0.53955 (0.16020)	0.77245 (0.35640)	0.53064 (0.12990)	0.78766 (0.38548)	0.50750 (0.17528)	0.71451 (0.39512)
Peak Velocity (mm/s)	178.925 (48.588)	319.391 (112.111)	196.816 (65.212)	309.844 (113.887)	229.545 (90.717)	354.923 (146.805)
Time to Peak Velocity (s)	0.22750 (0.10850)	0.25528 (0.11885)	0.19311 (0.06355)	0.29963 (0.24213)	0.16012 (0.05216)	0.24870 (0.15376)
Time after Peak Velocity (s)	0.31205 (0.08844)	0.51718 (0.25442)	0.33753 (0.07158)	0.48804 (0.17978)	0.34737 (0.13036)	0.46580 (0.24870)
% Time after Peak Velocity	57.6968 (9.2886)	65.4640 (7.0318)	62.4076 (3.1154)	62.6525 (10.6271)	66.04335 (4.7701)	63.6326 (6.9807)

Table 2: Control Conditions - Older

Dependent Variable	Contralateral		Midline		Ipsilateral	
	Near	**Far**	**Near**	**Far**	**Near**	**Far**
Movement Time (s)	0.54088 (0.08477)	0.76664 (0.09155)	0.58341 (0.10205)	0.74887 (0.16558)	0.46443 (0.09890)	0.66967 (0.11092)
Peak Velocity (mm/s)	159.2514 (31.6148)	269.032 (55.390)	162.2730 (36.4636)	270.9902 (45.2825)	224.4645 (69.8455)	319.5775 (75.9569)
Time to Peak Velocity (s)	0.22977 (0.05535)	0.27686 (0.04422)	0.23290 (0.08824)	0.28402 (0.05277)	0.17730 (0.06301)	0.22023 (0.03969)
Time after Peak Velocity (s)	0.31112 (0.08371)	0.48979 (0.07804)	0.35051 (0.08105)	0.46484 (0.13348)	0.28714 (0.10395)	0.44944 (0.09923)
% Time after Peak Velocity	56.1790 (10.9212)	62.71573 (5.5224)	61.3158 (8.8858)	61.1739 (5.9882)	60.4589 (13.2307)	65.32156 (6.2933)

Table 3: Block 1 - Immediate Recall – Young Group

Dependent Variable	Contralateral		Midline		Ipsilateral	
	Near	**Far**	**Near**	**Far**	**Near**	**Far**
Movement Time (s)	0.65671 (0.11287)	0.84165 (0.19706)	0.62823 (0.14296)	0.93540 (0.24478)	0.65358 (0.14707)	0.86645 (0.27425)
Peak Velocity (mm/s)	159.9347 (42.9347)	269.5797 (73.9893)	169.0740 (41.4724)	256.09787 (75.9771)	182.2859 (48.9451)	311.8893 (117.3226)
Time to Peak Velocity (s)	0.19270 (0.08427)	0.26355 (0.05667)	0.21355 (0.08951)	0.27091 (0.09669)	0.21165 (0.06999)	0.23358 (0.08178)
Time after Peak Velocity (s)	0.46401 (0.10122)	0.57809 (0.16629)	0.41470 (0.09221)	0.66449 (0.20466)	0.44195 (0.09765)	0.63288 (0.20213)
% Time after Peak Velocity	70.07486 (9.3260)	67.43597 (5.9785)	66.28315 (9.00728)	70.00516 (6.69779)	66.9804 (6.4446)	72.6695 (4.0781)
Amplitude Error (mm)	2.82059 (2.76955)	1.50567 (2.00534)	2.52798 (2.54182)	1.53137 (2.17329)	1.41266 (1.50451)	1.88136 (1.80206)
Directional Error (mm)	-1.33266 (1.5337)	0.29837 (0.86947)	0.18809 (1.2449)	-0.71164 (1.87216)	0.86625 (1.90672)	-0.42329 (1.5598)
Radial Error (mm)	4.4443 (2.09339)	3.5955 (1.0738)	3.81046 (1.71732)	3.94813 (1.49713)	3.32981 (1.17326)	3.34731 (1.48674)

Table 4: Block 1 - Immediate Recall – Older Group

Dependent Variable	Contralateral		Midline		Ipsilateral	
	Near	Far	Near	Far	Near	Far
Movement Time (s)	0.64378 (0.08209)	0.83931 (0.16759)	0.58735 (0.11180)	0.84602 (0.16633)	0.63533 (0.18457)	0.80512 (0.19346)
Peak Velocity (mm/s)	154.5922 (34.6176)	248.4412 (64.4833)	166.2043 (43.8252)	279.06919 (94.2030)	192.6687 (76.5752)	294.02511 (101.2286)
Time to Peak Velocity (s)	0.24094 (0.06546)	0.29165 (0.05689)	0.22296 (0.04739)	0.29288 (0.06095)	0.18493 (0.05165)	0.22650 (0.06059)
Time after Peak Velocity (s)	0.40283 (0.06759)	0.54770 (0.14047)	0.36441 (0.08757)	0.55316 (0.15439)	0.45039 (0.15547)	0.57862 (0.15683)
% Time after Peak Velocity	62.4639 (7.39611)	64.5144 (6.3549)	61.71975 (6.15462)	64.1860 (7.0815)	69.0131 (5.7582)	71.0803 (6.1405)
Amplitude Error (mm)	0.84438 (3.34417)	-0.63047 (6.67103)	2.0387 (1.81286)	1.53749 (6.3366)	0.29715 (3.06597)	-0.81173 (5.99139)
Directional Error (mm)	-2.26294 (2.4937)	-0.21017 (2.52496)	0.36996 (2.2977)	-0.04227 (1.5457)	1.89951 (2.3260)	0.71476 (2.39321)
Radial Error (mm)	4.88817 (2.98740)	6.68305 (4.42946)	3.92019 (1.51188)	6.52552 (3.69396)	4.53334 (2.0906)	5.72877 (4.7297)

Table 5: Block 1 – Delay Recall – Young Group

Dependent Variable	Contralateral		Midline		Ipsilateral	
	Near	**Far**	**Near**	**Far**	**Near**	**Far**
Movement Time (s)	0.65222 (0.17902)	0.88866 (0.265057)	0.62686 (0.17764)	0.92990 (0.41033)	0.59769 (0.18557)	0.85501 (0.31639)
Peak Velocity (mm/s)	165.5456 (51.3968)	234.2111 (74.5937)	171.16024 (53.3499)	255.6946 (115.6468)	181.8429 (58.8429)	302.6557 (91.6266)
Time to Peak Velocity (s)	0.21245 (0.08714)	0.26314 (0.10499)	0.21167 (0.07831)	0.30006 (0.14532)	0.18806 (0.095437)	0.27840 (0.11690)
Time after Peak Velocity (s)	0.43976 (0.140276)	0.62551 (0.21473)	0.41519 (0.16278)	0.62985 (0.28268)	0.40965 (0.14248)	0.57658 (0.22428)
% Time after Peak Velocity	66.72164 (10.2025)	69.7982 (8.36123)	63.9716 (10.2789)	67.80115 (6.14857)	67.22633 (10.77423)	66.07642 (7.0602)
Amplitude Error (mm)	2.5331 (3.71872)	1.7842 (4.57227)	3.13127 (4.5383)	1.56625 (1.98236)	2.00383 (3.9582)	-0.26039 (5.07731)
Directional Error (mm)	-1.70741 (3.26187)	0.05323 (3.24082)	-0.64361 (2.3448)	-1.05702 (2.99623)	3.04475 (3.16004)	-0.59473 (2.9423)
Radial Error (mm)	6.24117 (2.95632)	5.58023 (2.4708)	5.34348 (3.42045)	4.16927 (2.62470)	6.07295 (2.09911)	5.74533 (2.55807)

Table 6: Block 1 – Delay Recall – Older Group

Dependent Variable	Contralateral		Midline		Ipsilateral	
	Near	**Far**	**Near**	**Far**	**Near**	**Far**
Movement Time (s)	0.66449 (0.07514)	0.86932 (0.18823)	0.65606 (0.08794)	0.90350 (0.17887)	0.65141 (0.13732)	0.88430 (0.15980)
Peak Velocity (mm/s)	136.6819 (23.7586)	230.7836 (50.8025)	139.1367 (23.6661)	233.4404 (49.2147)	155.8700 (49.2537)	251.6220 (86.6219)
Time to Peak Velocity (s)	0.22321 (0.04869)	0.29341 (0.05799)	0.22321 (0.08182)	0.30553 (0.06302)	0.20469 (0.07186)	0.28306 (0.13999)
Time after Peak Velocity (s)	0.44126 (0.044126)	0.57590 (0.15601)	0.43281 (0.07525)	0.59795 (0.15586)	0.44672 (0.14629)	0.60126 (0.17648)
% Time after Peak Velocity	65.98734 (4.2372)	65.5103 (6.74893)	66.08928 (9.7869)	65.31912 (7.0919)	67.90196 (9.9784)	67.41261 (13.1355)
Amplitude Error (mm)	0.67834 (3.2254)	1.01005 (4.7847)	4.13669 (3.68549)	1.98527 (8.35098)	1.68451 (3.1165)	0.56282 (5.61878)
Directional Error (mm)	-2.00721 (2.1533)	0.65598 (3.5858)	-0.76964 (1.53797)	-0.59642 (1.89922)	1.35489 (3.13479)	2.06440 (1.92187)
Radial Error (mm)	5.15328 (1.7498)	6.6471 (3.40247)	5.15138 (3.1393)	7.27258 (5.47388)	5.03292 (2.5752)	6.65906 (2.5558)

Table 7: Block 2 – Immediate – Young Group

Dependent Variable	Contralateral		Midline		Ipsilateral	
	Near	**Far**	**Near**	**Far**	**Near**	**Far**
Movement Time (s)	0.57864 (0.21391)	0.81957 (0.31087)	0.58655 (0.28297)	0.79476 (0.38277)	0.64294 (0.22020)	0.73698 (0.33889)
Peak Velocity (mm/s)	181.6934 (55.6039)	294.8009 (91.3666)	188.40555 (68.5248)	313.2716 (113.5931)	203.7404 (67.7902)	369.7886 (139.4695)
Time to Peak Velocity (s)	0.18588 (0.02529)	0.29028 (0.13776)	0.17988 (0.03369)	0.31290 (0.20986)	0.17309 (0.08141)	0.25783 (0.18252)
Time after Peak Velocity (s)	0.39275 (0.20657)	0.50751 (0.18597)	0.40093 (0.30205)	0.47233 (0.19524)	0.45543 (0.19604)	0.47915 (0.16825)
% Time after Peak Velocity	65.14135 (8.2749)	62.87859 (9.9817)	63.02268 (13.2319)	61.15422 (9.3975)	68.8911 (11.6637)	66.00354 (6.7389)
Amplitude Error (mm)	1.60809 (2.2966)	0.13256 (2.65767)	2.64391 (1.80617)	0.86540 (2.61655)	0.98857 (2.12100)	0.88056 (3.40798)
Directional Error (mm)	-1.10714 (2.08317)	0.16859 (2.2272)	-0.10179 (1.10678)	-0.17191 (2.51902)	1.30532 (2.1653)	0.33009 (2.1224)
Radial Error (mm)	3.84503 (2.11409)	4.21238 (2.4524)	4.26700 (1.5097)	4.25702 (1.93412)	3.90501 (1.6234)	4.03117 (1.7867)

Table 8: Block 2 – Immediate Recall – Older Group

Dependent Variable	Contralateral		Midline		Ipsilateral	
	Near	**Far**	**Near**	**Far**	**Near**	**Far**
Movement Time (s)	0.58762 (0.10415)	0.83839 (0.19998)	0.57509 (0.09965)	0.75933 (0.12933)	0.57467 (0.11460)	0.68970 (0.107874)
Peak Velocity (mm/s)	166.0121 (37.2590)	269.5905 (43.9718)	167.9355 (40.9355)	273.4338 (44.5063)	208.3464 (41.0383)	325.228 (51.0676)
Time to Peak Velocity (s)	0.22102 (0.04529)	0.27120 (0.03461)	0.20523 (0.05917)	0.28237 (0.06170)	0.17525 (0.03488)	0.23808 (0.04776)
Time after Peak Velocity (s)	0.36657 (0.10320)	0.56717 (0.19807)	0.36985 (0.11856)	0.47697 (0.16265)	0.39944 (0.12721)	0.45160 (0.09316)
% Time after Peak Velocity	60.9873 (7.3502)	65.89613 (6.7621)	62.91588 (11.7466)	61.62565 (12.2458)	67.8456 (8.2883)	64.99659 (7.07033)
Amplitude Error (mm)	1.44723 (2.64215)	0.42319 (6.2533)	2.10976 (3.51442)	1.91687 (5.19199)	-0.04591 (2.43177)	-0.21890 (3.3197)
Directional Error (mm)	-0.75073 (2.7640)	-0.78760 (3.4978)	-0.41788 (1.70257)	-1.39947 (2.5148)	1.11876 (2.4775)	0.86866 (1.6967)
Radial Error (mm)	4.7805 (2.5929)	6.15962 (4.62282)	4.24770 (1.68757)	6.21028 (3.20969)	4.06917 (1.9254)	4.65904 (2.13138)

Table 9: Block 2 – Delay Recall – Young Group

Dependent Variable	Contralateral		Midline		Ipsilateral	
	Near	**Far**	**Near**	**Far**	**Near**	**Far**
Movement Time (s)	0.65237 (0.14061)	0.95162 (0.4882)	0.63722 (0.18623)	0.81465 (0.32051)	0.70789 (0.23742)	0.84396 (0.25976)
Peak Velocity (mm/s)	184.252 (56.2491)	265.317 (91.1104)	189.1190 (66.0224)	296.0064 (99.1756)	201.3301 (60.0814)	328.062 (123.1025)
Time to Peak Velocity (s)	0.20837 (0.06657)	0.25946 (0.076404)	0.23113 (0.0987)	0.27473 (0.12080)	0.16071 (0.03477)	0.25033 (0.11849)
Time after Peak Velocity (s)	0.44398 (0.12055)	0.69215 (0.42281)	0.40609 (0.10936)	0.53992 (0.21133)	0.54719 (0.25239)	0.59361 (0.17367)
% Time after Peak Velocity	66.03459 (9.7968)	69.44441 (5.8238)	63.71435 (8.6841)	65.91747 (4.8379)	73.70681 (10.3565)	70.72363 (6.58972)
Amplitude Error (mm)	1.76854 (3.5987)	1.01373 (4.4909)	2.2995 (4.60201)	1.20832 (2.6837)	0.26678 (2.24412)	0.03321 (2.6876)
Directional Error (mm)	-2.31049 (2.4414)	-0.47593 (1.99358)	-0.23733 (1.06821)	-0.26365 (2.95289)	1.26107 (2.1579)	-0.04294 (1.23256)
Radial Error (mm)	4.79056 (2.9833)	5.65134 (2.31391)	4.80264 (2.99505)	5.05337 (1.53579)	3.62695 (1.42144)	3.85772 (1.5887)

Table 10: Block 2 - Delay Recall – Older Group

Dependent Variable	Contralateral		Midline		Ipsilateral	
	Near	**Far**	**Near**	**Far**	**Near**	**Far**
Movement Time	0.61856 (0.07911)	0.85038 (0.06796)	0.64405 (0.09485)	0.78223 (0.1260)	0.61298 (0.08587)	0.81029 (0.0552)
Peak Velocity	157.82683 (44.8419)	241.55187 (35.6412)	148.0826 (26.5026)	242.98574 (49.5118)	186.2181 (83.2181)	283.07713 (42.3910)
Time to Peak Velocity	0.23534 (0.06436)	0.29954 (0.04348)	0.23030 (0.07439)	0.30104 (0.06462)	0.17349 (0.04861)	0.24067 (0.04918)
Time after Peak Velocity	0.38321 (0.11740)	0.55084 (0.04332)	0.41374 (0.09765)	0.48117 (0.13674)	0.4395 (0.09754)	0.56965 (0.06935)
% Time after Peak Velocity	60.84627 (12.9661)	64.72251 (3.4425)	63.61021 (10.67355)	60.33996 (9.9167)	70.42665 (8.60087)	69.89019 (5.01361)
Amplitude Error	2.40969 (2.4853)	2.1001 (4.6069)	3.45026 (4.5835)	1.82087 (8.03675)	- 0.114113 (3.42687)	2.57934 (3.7243)
Directional Error	-2.27482 (2.2238)	-0.14296 (3.7187)	-0.72924 (1.1979)	-0.90493 (1.8286)	-0.00712 (4.40155)	2.48467 (3.446)
Radial Error	5.4183 (1.7726)	5.96343 (2.72055)	5.71291 (2.56639)	7.90102 (5.03942)	5.37634 (2.3465)	5.93043 (2.6599)