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ABSTRACT

MOTOR PLANNING
FOR REACH MEMORIZATION TASK IN 3D SPACE

by
Atul Narkhede

Arm reaching towards remembered targets in three-dimensional space was analyzed. The aim of the project was to test whether various amounts of visual feedback, in combination with constant forces applied to the arm during reaching would affect the magnitude and direction of the reaching errors. The robotic arm (Haptic Master, Moog Inc) recorded the spatial position of the pointer attached to its end effector, thus tracking the movement of the subject's arm. Three haptically rendered targets at different points in space were presented to the subjects using stereo virtual environment. The simulation was programmed using Visual C++ and OpenGL. Eight subjects were asked to remember the position of the target and then to reach the target with the pointer. Three different types of visual feedback were used, with full vision (Vision), with the target disappearing immediately before the movement onset (No Vision) and one second after the movement onset (Intermediate Vision). In all three visual conditions, the subjects arm was visible during the movement. In addition, an external force opposing gravity was applied in half of the trials. Pointing errors and different parameters of movement kinematics were analyzed and compared across conditions. It was observed that both the magnitude and the direction of reaching errors were affected by the amount of visual information available during the movement, as well as by the partial gravity compensation provided by the robot.

MOTOR PLANNING
FOR REACH MEMORIZATION TASK IN 3D SPACE

by
Atul Narkhede

A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Biomedical Engineering

Department of Biomedical Engineering

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FOR REACH MEMORIZATION TASK IN 3D SPACE

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This thesis is dedicated to Narkhede family.

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CHAPTER 1

INTRODUCTION

The objective of this thesis was to identify differences in the kinematics of pointing movements that correspond to variations in the sensory environment in which they are performed.

In 1981, Morasso found that pointing to visually presented targets; a central command is formulated in terms of trajectories of the hand in space. Morasso observed that the hand trajectories produced single peaked tangential velocity curve (bell shaped) whereas the joint angular curves varied significantly for different movements.

In 1993, Darling and Miller showed that subjects made significant distance errors while pointing to remembered locations. They found out that the subjects transformed kinesthetically defined hand locations into a visual coordinate system when vision was available. They also found out that subjects were accurate in locating the targets in purely kinesthetic conditions.

In 1998, Adamovich et al. found that human subjects can use diverse sensory information to achieve comparable final accuracy when pointing to targets, but the details of the strategies used differ based on the kind of feedback available. Kinesthetic target presentation enables the implementation of mixture of strategies. The strategies they suggested were using adequate arm configuration stored in memory that was assumed during target presentation and use synergistically coordinated joint angles so that accuracy is achieved by focusing on a specific end point. In case of the visual presentation of the target, they suggest, that errors may be due to visual processing rather

than motor planning and implementation. In addition, this study, as well as other studies of reaching to remembered targets in 3D space by the same authors (see, for example, Poizner et al., 1986) have found some evidence of systematic shifts in the arm endpoint final position relative to the target. In particular, they observed significant undershoots in the vertical directions for subjects with Parkinson's disease and significant overshoots in the vertical direction for neurologically healthy age-matched controls.

For accurate pointing to remembered targets visually defined coordinates stored in visual-spatial memory must be compared to the arm end point computed from proprioceptive feedback (Berkinblit et al. 1995; Darling and Miller 1993; Soechting and Flanders 1989 (a and b)).

In 1989a, Soechting and Flanders found that subjects had a reasonably accurate visual representation of target location and were able to effectively use kinesthetically derived information about target location. They also suggested that errors in pointing resulted from errors in the sensorimotor transformation from the visual representation of the target location to the kinematic representation of the arm movement.

In 1995, Berkinblit and colleagues found that under different visual conditions subjects controlled motion along the three axes independently of each other. This suggests that the errors made in each axis are independent on other axes. Errors could be position or angles. In 2006, Beurze et al. found that initial hand position had an effect on pointing errors when pointing to a remembered target. In this thesis we use a physical reference point so that these initial errors are reduced.

In 1998, Vindras et al. did a study that proved that the aimed hand movements are planned in terms of distance and direction. In 1999, Messier and Kalaska further found

out that in reaching movements to memorized visual target locations the direction and extent of movements are planned in parallel over time.

In 2008, a research done by Izawa et al. showed that humans re-optimize their movement trajectories in the changed environments to maximize performance; this is the goal of adaptation. In 2009, Bourgeois, J. and Coello, Y. showed that there are spatial errors when the force required in reaching a visual target is modified.

In this thesis there were variations in visual feedback conditions in which the target was visible for the full course of the movement (baseline); an intermediate stage in which the target disappears one second after the onset of the movement (after); and the third where the target disappears two seconds before the onset of the movement (before). There is also a variation in the external force (gravity); the movement was assisted or unassisted. The variation in external force was applied to the latter two visual conditions. Three targets are placed at different positions in virtual 3D space and reach action is made using a haptic robotic arm system with no tactile feedback of the target.

The hypothesis is that there are differences in errors and kinematic parameters when movement is made in different conditions. It is expected to observe bell shaped curves for tangential velocities. It is also expected to observe errors in positions independently in all three axes. If there is no visual feedback of the target as after and before conditions, it is expected to have higher elevation error and z position errors when the arm is partially supported against gravity than when it is unassisted.

CHAPTER 2

METHODS

Interactive virtual reality is an engaging and adaptable tool in which subjects can practice and acquire motor skills. The technology used here allows the experimenter to collect precise kinematic and kinetic outcome measure of a subject's current sensorimotor task. This chapter describes the instruments, interfaces and conditions used for the experiment and the procedure.

2.1 Instruments

Haptics, meaning sense of touch, is an emerging technology allowing touch enabled interaction with virtual objects. Haptics along with 3D computer graphics gives the user not only the visual information but also simulates the tactile feeling of a virtual object giving a more complete virtual experience. To produce this experience in the experiment *Haptic Master*™ (HM) (Moog Inc., Netherlands) robot, a 3D high resolution display, 3D glasses, an *Infra Red* (IR) transmitter, a starting point reference stand and interfaces are used.

HM is a, three degree of freedom, force controlled robot arm through which high fidelity haptic performance is produced. It records precisely the kinematic parameters of speed, positions and forces in the x, y and z directions. HM can be programmed to simulate haptically rendered environments. This is done by running the admittance control loop in the haptic server, a dedicated computer that comes with the HM, this frees the user, and haptic client, from all real time performance constraints.

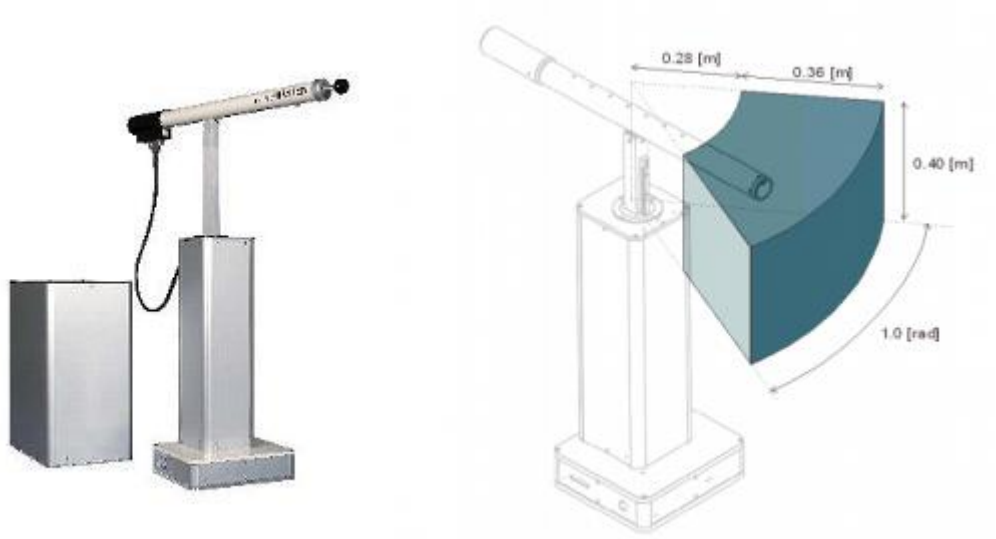

Figure 2.1 Haptic Master Robot.

Source: Moog Inc. http://www.haptist.com/HapticMaster.html and http://www.ngohaibac.com/the-hapticmaster-a-good-device-for-admittance-control/, accessed November 30, 2010.

Stereoscopic glasses were used to enhance depth perception and present movement targets to the subjects in a three dimensional stereo working space. CrystalEyes™ stereoscopic glasses were used to present three dimensional virtual environments. This process employs two graphic buffers, one for the left eye, another one for the right eye. CrystalEyes stereoscopic glasses block one eye at a time with the same frequency as computer refresh rate. This synchronization allows the right eye to see the right graphic buffer, and the left eye to see the left graphic buffer, which provides a three dimensional stereo effect. The IR transmitter synchronizes the glasses with the display. It allows the 3D glasses to be wireless. Since it is IR based, the experimenter has to make sure that the glasses are in its range at all times.

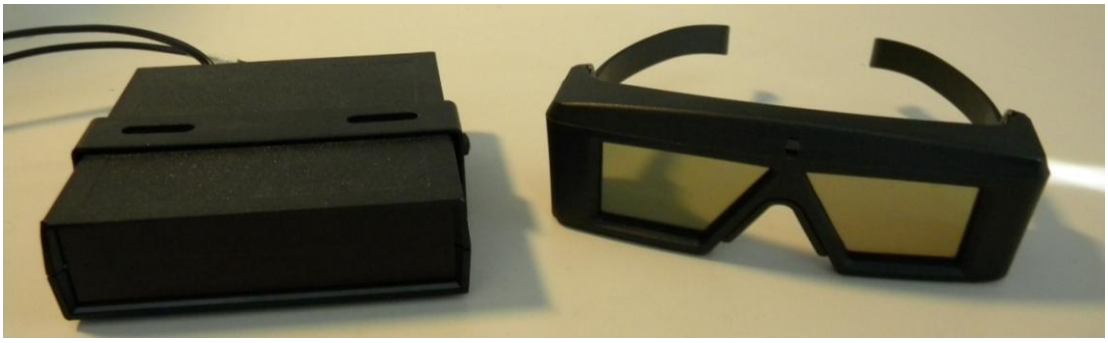

Figure 2.2 Infra Red Transmitter with CrystalEyes Stereoscopic Glasses.

The starting point reference stand is used to mark the physical starting position in space of the trials.

Figure 2.3 Starting Point Reference Stand (x marks the starting point).

2.2 Interfaces

Interfaces were developed so that it interacting with HM and its environment is easy and comfortable. The hardware interface is a pointing device that gets attached to the sensor

tip of the haptic master. The software interface is a software code that drives the HM as needed.

The hardware interface, a pointing device, is essentially a pen with white tape at the tip fastened with screws to an aluminum frame that attaches to the sensor end of the haptic master with the help of screws. The white tape was taped to the tip so that the subject can see the tip at all times.

Figure 2.4 Pointer that attaches to haptic master.

The software interface, a *Visual C++* (VC++) code, was developed to control HM, display virtual 3D targets and display a *graphical user interface* (GUI) to specify the environment of the haptic master. Since the objective was to reach a remembered target the environment was a dark empty space so that no reference is available for subjects to help them remember the location of the target. Figure 2.5 shows the parameters that define the environment of the HM. For this thesis the parameters specified are inertia, damping coefficient, gravity, haptic master height control, number of targets, starting delay, disappear delay, trial duration, and save at location.

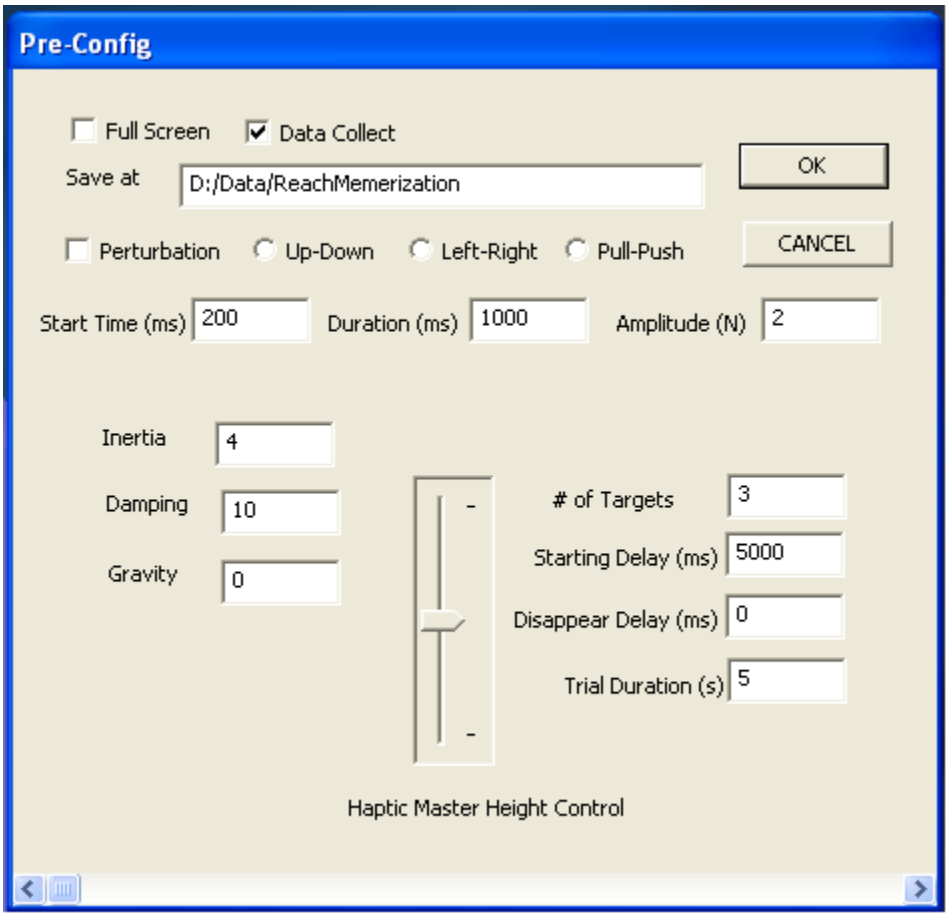

Figure 2.5 GUI to define parameters of HM.

The inertia, damping coefficient and gravity define global forces within the virtual environment presented by the HM. The inertia defines the virtual mass of the pointer. The damping coefficient defines the resistance in movement of the haptic arm. Gravity defines the force with which the haptic arm is pulled towards (denoted by positive sign) or pushed away (denoted by negative sign) from the earth. These conditions are explained in Section 2.3. The haptic master height control was used to adjust the initial height before the start of the trial. Between each condition HM was recalibrated in order to return it to its default position. The starting point reference stand had the same X-Y position, as the default HM position, but at different height or Z position. HM height

control adjusts the initial height at the start. The number of targets defines the number of virtual targets appearing on the display. Trial duration the time in which the subject is allowed to move, this period is marked by two ding sounds. Starting delay is the time, after trial starts, after which the subject is allowed to move; it is the time for which the subject looks at the target. Disappear delay is the time, after trial starts, after which the target disappears. Figure 2.6 illustrates the starting delay, disappear delay and the times when the two ding sounds appear on the velocity curve.

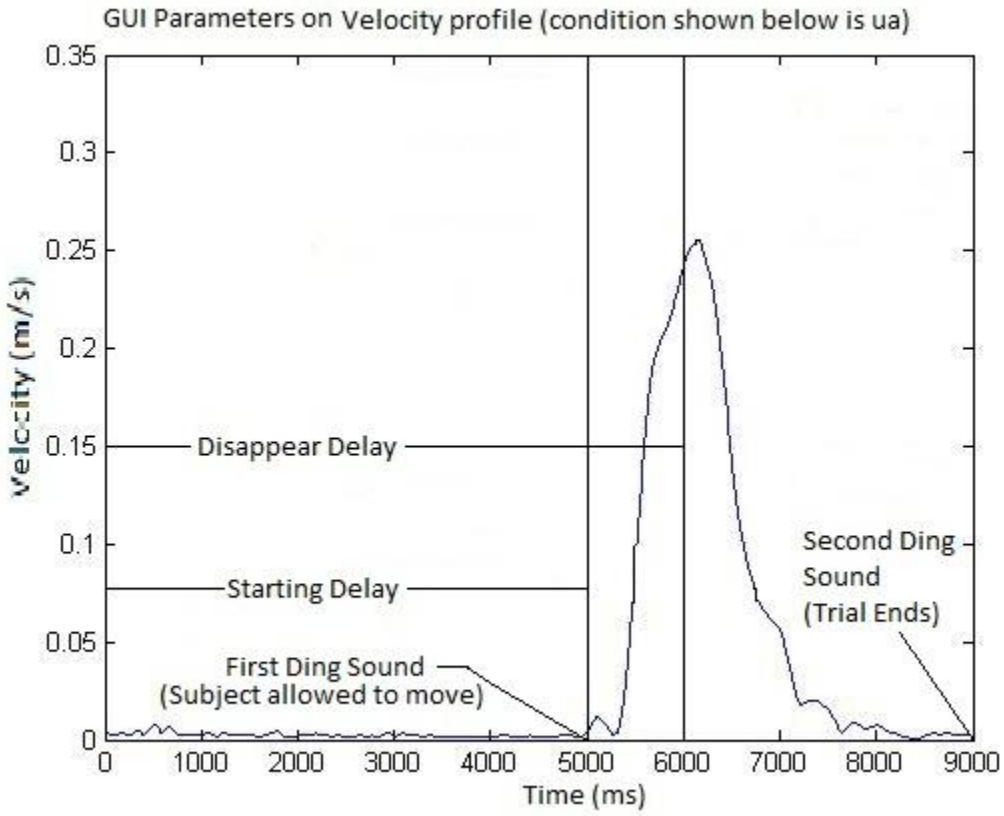

Figure 2.6 Starting Delay, Disappear Delay and the two ding sounds marked over the velocity profile.

2.3 Conditions

During the experiment there were five variations in conditions that were applied to the haptic master environment *base line* (bl), *unassisted before* (ub), *unassisted after* (ua), *assisted before* (ab) and *assisted after* (aa). The conditions introduced in Section 2.2 are explained further in this section. The following table gives a summary of GUI values for different conditions. The conditions are explained in detail further ahead.

Table 2.1 Summary of Different Conditions and the Values of GUI Parameters

Conditions	bl	ub	ua	ab	aa
Inertia (kg)	4	4	4	4	4
Damping (N*sec/m)	10	10	10	10	10
Gravity (N)	0	0	0	-5	-5
# of Targets	3	3	3	3	3
Starting Delay (ms)	1000	5000	5000	5000	5000
Disappear Delay (ms)	5000	-2000	1000	-2000	1000
Trial Duration (s)	3	3	3	3	3

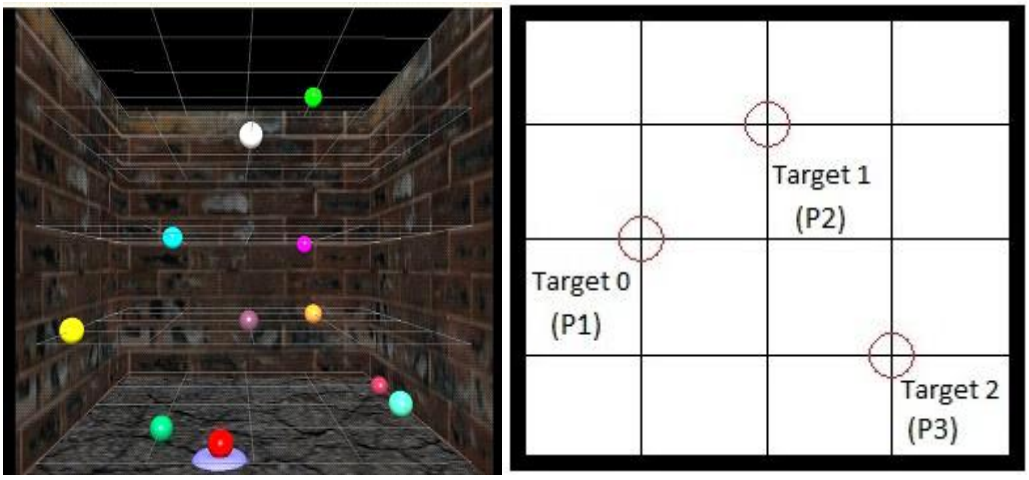

Figure 2.7 Left panel: stereo virtual environment to study three-dimensional reaching. Right panel: positions of three virtual targets selected for this study (frontal view).

The first condition bl, is when the target is visible throughout the trial. The starting delay is set to 1000 *microseconds* (ms), meaning the subject looks at the target for 1000 ms, after which the subject is allowed to move. Disappear delay is set to 5000 ms, meaning the target is visible for 5000 ms after the trial starts, that is the trial duration of 5 seconds. Since the distance between eyes varies across subjects, the target is perceived in different plane by different subjects, thus this condition becomes the baseline measurement for the subject.

The second condition ub, is when the target disappears before the subject is allowed to move, and the movement is unassisted. Disappear delay is -2000 ms (negative sign indicates its time before the subject is allowed to move) and the starting delay is 5000 ms.

The third condition ua, is when target disappears after the subject is allowed to move, and the movement is unassisted. Disappear delay is 1000ms (positive sign indicates its time after the subject is allowed to move) and the starting delay is 5000 ms.

The fourth condition ab, is when target disappears before the subject is allowed to move, and the arm is partially supported against gravity. The assistive force is equal to 5 N. Disappear delay is -2000 ms and the starting delay is 5000 ms.

The fifth condition aa, is when target disappears after the subject is allowed to move, and the movement is assisted, meaning the value of assistive force is -5 N. Disappear delay is 1000 ms and the starting delay is 5000 ms.

2.4 Experimental Procedure

2.4.1 Subjects

There were eight healthy subjects participating in the experiment. A healthy subject is defined as a human with no neurological disorders, cardiovascular diseases, diabetes, upper extremity amputation, orthopedic condition like shoulder or elbow tendonitis, rotator cuff tears, impingement syndrome, visual impairment like inability to tolerate stereo vision or inability to see with one or both eyes and visually evoked seizures. All subjects signed a consent form approved by the New Jersey Institute of Technology's Institutional Review Board to take part in the study.

2.4.2 Procedure

First the experimenter provides the subject with an overview of the experiment. The starting point is established by the experimenter then running an executable file that recalibrates the HM setting to its default position and displays GUI on screen. The parameters are set on the GUI and pointer is set at the starting point reference stand. The subject is asked to sit in a chair in upright position, with the 3D glasses on his eyes and

hold the pointer. Next the experimenter hits the spacebar and a virtual 3D target appears on the screen. This is when the data collection starts. The subject looks at the target during the starting delay after which s/he can move. The instance that the subject is allowed to move is marked by a computer generated ding sound. The subject reaches to and touches the virtual 3D target where s/he perceives it, with the pointer tip, making the reach action. There is a second ding sound, after three seconds of the first, which marks the end of data collection. The subject is expected to reach the perceived target in the time between the two ding sounds. Before starting the next trial the subject brings the pointer back to the starting point. The same is repeated for all three targets, ten trials per target, i.e., 30 trials per condition. The sequence for conditions was same for all the subjects. It is listed here in the order they were applied bl, ub, ab, ua, aa.

Figure 2.8 is a pictorial representation of the parameters of hand motion defined over the velocity profile for reach action. The on-set and off-set of reach action is marked at 3% value of peak velocity. It is within these limits of the velocity that significant movement is said to have been made.

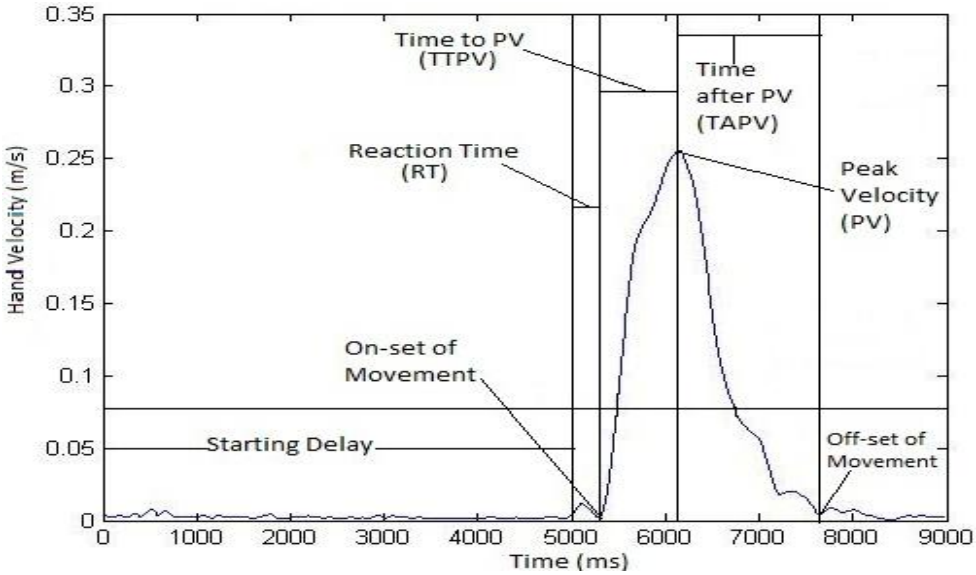

Figure 2.8 Parameters of hand movement analyzed in the study.

2.5 Statistical Analysis

The objective of the analysis was to find possible effects of visual feedback and partial gravity compensation on the movement kinematics and reaching errors of a three-dimensional arm reaching performed in a stereoscopic virtual environment. Three way analysis of variance (ANOVA) tests, with repeated measures factors Feedback (after (a), before (b)), Gravity (unassisted (u), assisted (a)) and Target (P1, P2, P3) were performed to test for statistically significant differences in movement kinematics and reaching errors across conditions. The analysis was performed on the following parameters of movement units, time to peak velocity and time after peak velocity. In addition the following components of pointing errors were analyzed: elevation error, x position error, y position error and z position error. The effects of visual feedback, constant external force, and target location were considered. By including the factor Feedback, into the statistical design, two modes of visual feedback were compared, 'b' denoting condition where the target would disappear before movement onset, and 'a' denoting condition where the target would disappear one second after the signal to move. By including factor Gravity into the statistical design, the potential effect of partial gravity compensation was analyzed, with gravity-assisted reaching denoted as 'a' and unassisted reaching denoted as 'u'. In the statistical outcome tables targets were labeled as P1 (target 0), P2 (target 1), and P3 (target 2). The effect of target location on movement parameters and reaching errors were also analyzed.

CHAPTER 3

RESULTS

This chapter defines the different parameters of the hand trajectory and pointing errors. It also presents the results of experiments individually for each kinematic parameter or for each error component for all the subjects and all conditions. Figure 3.1 is a graph showing reach action under different conditions. The dotted curves are the trajectory of the pointer in Z (vertical) axis and the solid curves are the velocity profiles for the same. The first bell shaped curve shows the reach action and the second (as seen in the red curve only) shows return of the pointer to the starting point reference.

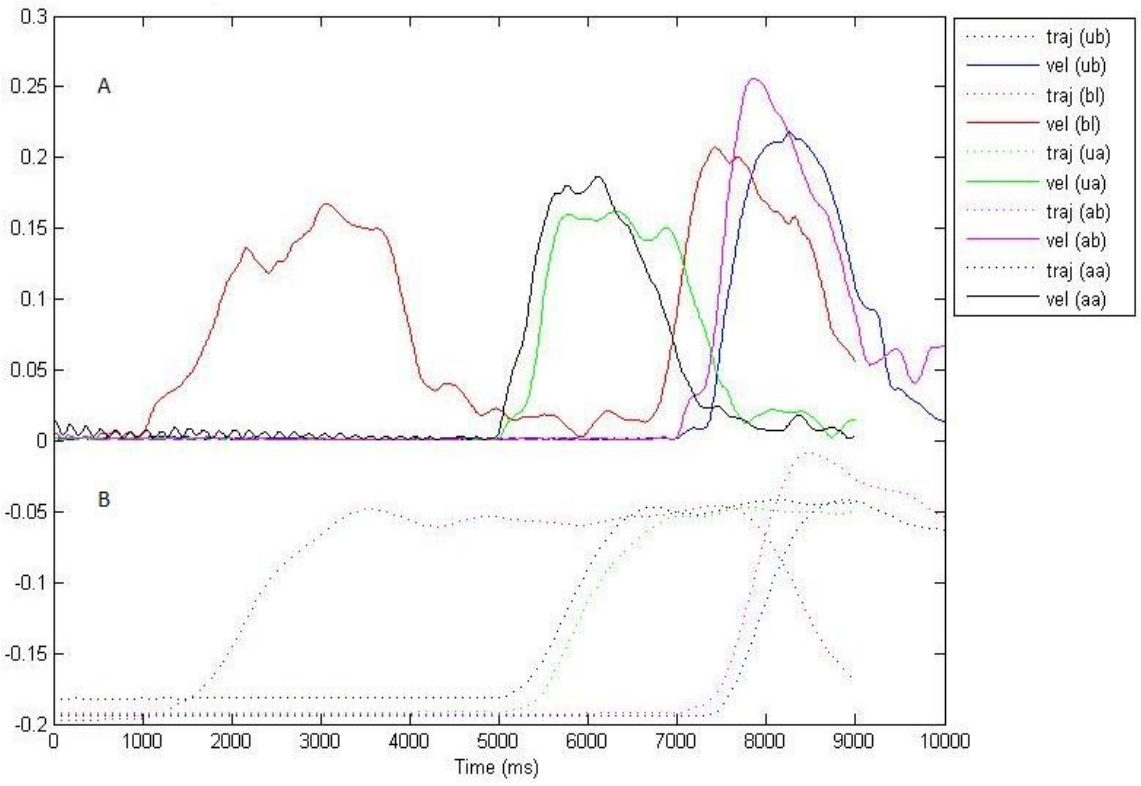

Figure 3.1 A. Velocity Profiles (vel) plotted over time for different conditions and B. Trajectories (traj) in Z axis (vertical movement).

3.1 Peak Velocity

Peak velocity is defined as the maximum velocity achieved when performing the reach movement towards the target. Figure 3.2 is a summary of peak velocities for all three targets and all five conditions. As can be observed in the graph, there is a decrease in peak velocity from target 0 to 2. Also, the after conditions (ua and aa) have higher peak velocities than the before conditions (ub and ab).

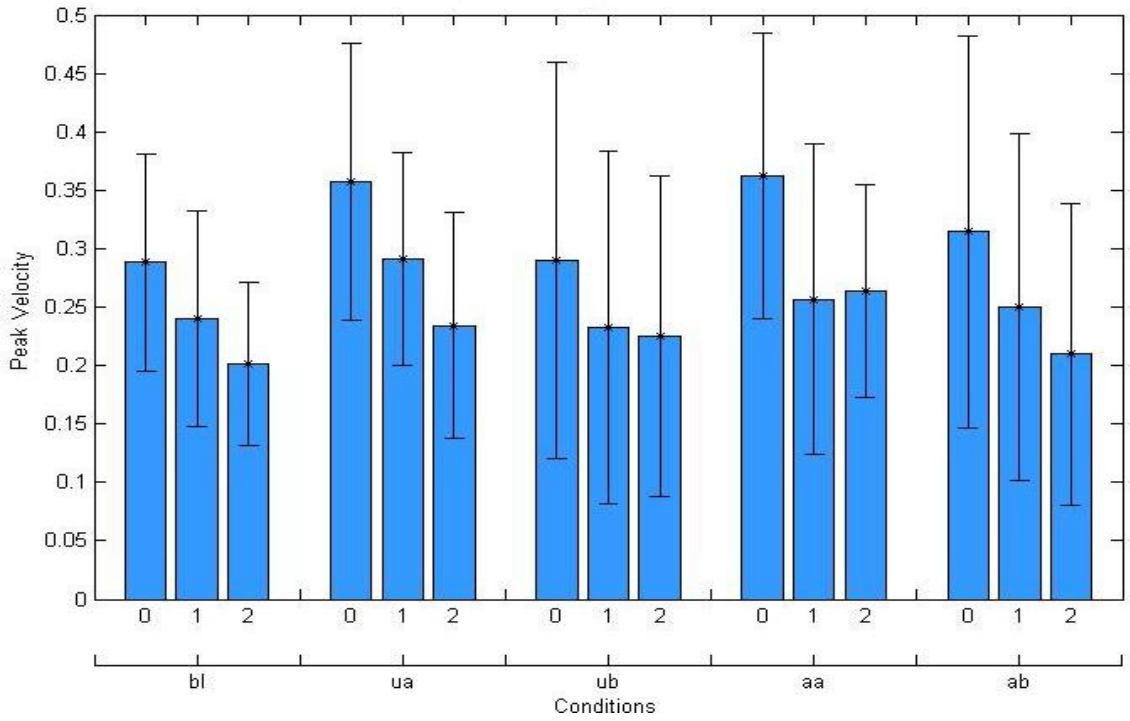

Figure 3.2 Summary of Peak Velocities for all subjects, each bar represents a target and each cluster represents different condition (bl: baseline; ua: unassisted after; ub: unassisted before; aa: assisted after; ab: assisted before).

Table 3.1 Summary of ANOVA Analysis on Peak Velocity

ANOVA Table for Peak Velocity

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	7	.207	.030				
Feedback	1	.040	.040	6.673	.0363	6.673	.603
Feedback * Subject	7	.042	.006				
Gravity	1	.001	.001	.065	.8058	.065	.056
Gravity * Subject	7	.055	.008				
Targets	2	.165	.082	29.331	<.0001	58.662	1.000
Targets * Subject	14	.039	.003				
Feedback * Gravity	1	4.942E-4	4.942E-4	.218	.6547	.218	.069
Feedback * Gravity * Subject	7	.016	.002				
Feedback * Targets	2	.003	.002	3.240	.0698	6.479	.515
Feedback * Targets * Subject	14	.007	.001				
Gravity * Targets	2	.002	.001	.819	.4608	1.639	.158
Gravity * Targets * Subject	14	.019	.001				
Feedback * Gravity * Targets	2	.010	.005	2.386	.1283	4.773	.393
Feedback * Gravity * Targets * Subject	14	.028	.002				

As can be seen by observing the p-values in Table 3.1 and Figure 3.2, there are effects of feedback on the peak velocity. The effects of feedback are significant (also shown by Table 3.2 and Figure 3.3). There are combined effects of feedback and gravity (shown in Table 3.3 and Figure 3.4), but they are not significant. With increased number of subjects the differences might be statistically significantly.

Table 3.2 Effects of Feedback on Peak Velocity

Means Table for Peak Velocity
Effect: Feedback

	Count	Mean	Std. Dev.	Std. Err.
a	48	.294	.077	.011
b	48	.253	.082	.012

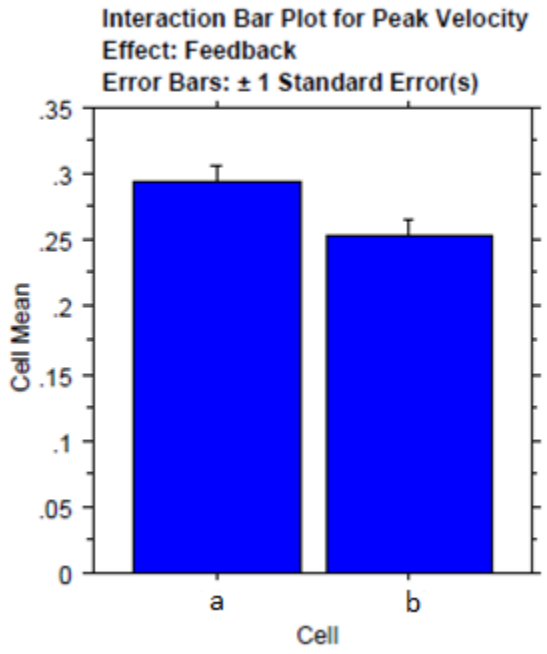

Figure 3.3 Effects of Feedback on Peak Velocity.

Table 3.3 Effects of Feedback and Gravity on Peak Velocity

Means Table for Peak Velocity
Effect: Feedback * Gravity

	Count	Mean	Std. Dev.	Std. Err.
a, u	24	.294	.075	.015
a, a	24	.294	.082	.017
b, u	24	.249	.077	.016
b, a	24	.258	.087	.018

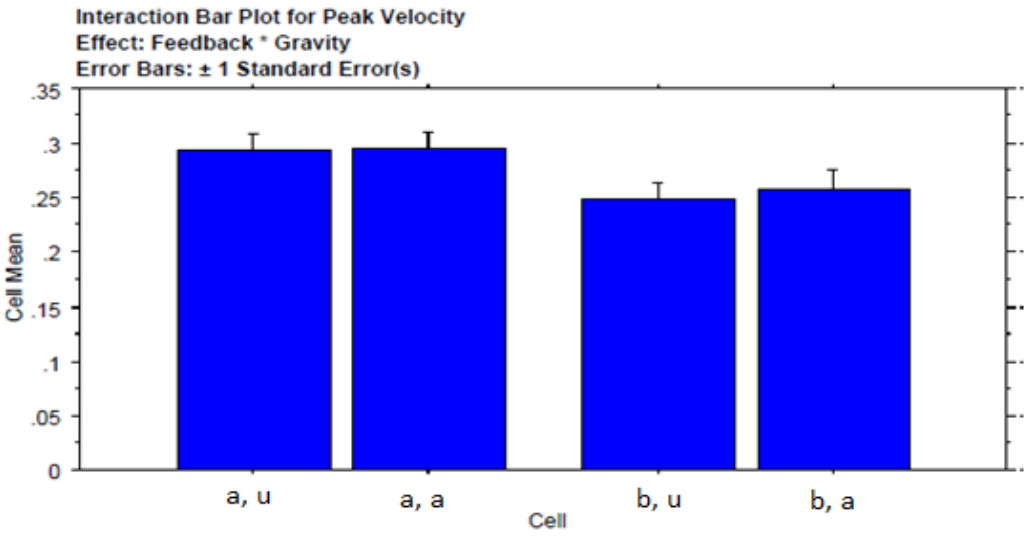

Figure 3.4 Effects of Feedback and Gravity on Peak Velocity.

3.2 Movement Units

Movement units are defined as the number of peaks on the velocity curve from on-set to off-set of the reach action. It is an indicator of the smoothness of the movement, the fewer the movement units, the smoother the reach action is. The following three velocity curves show the differences in velocity profiles when there are differences in movement units.

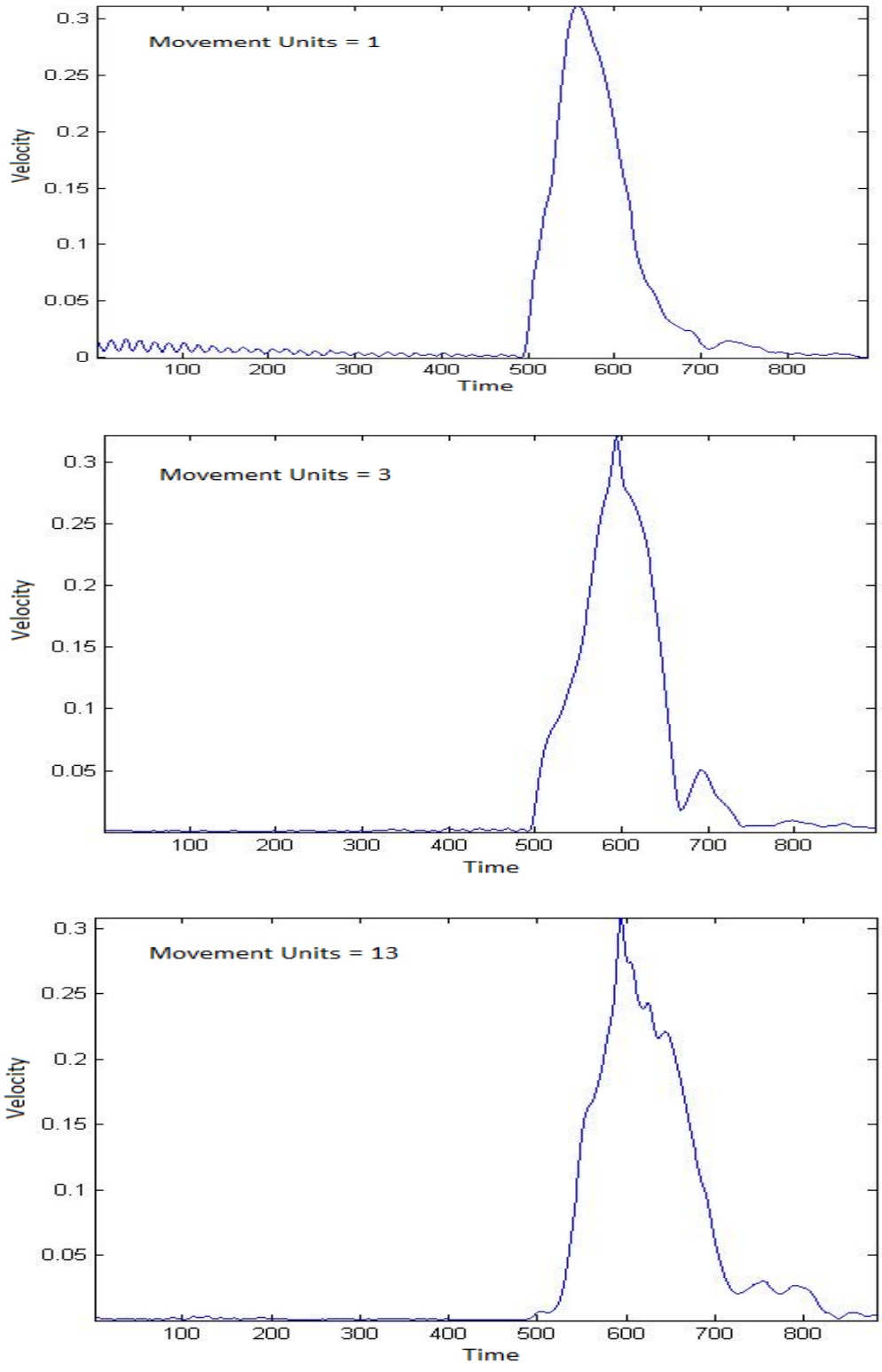

Figure 3.5 Velocity profiles showing differences in movement units.

It can be seen that as the number of movement units increases the smoothness in the velocity profiles decreases. Shown below is summary of the movement units for all three targets and for all different conditions. It can also be seen that the subjects made smoother movements in after conditions than in before conditions.

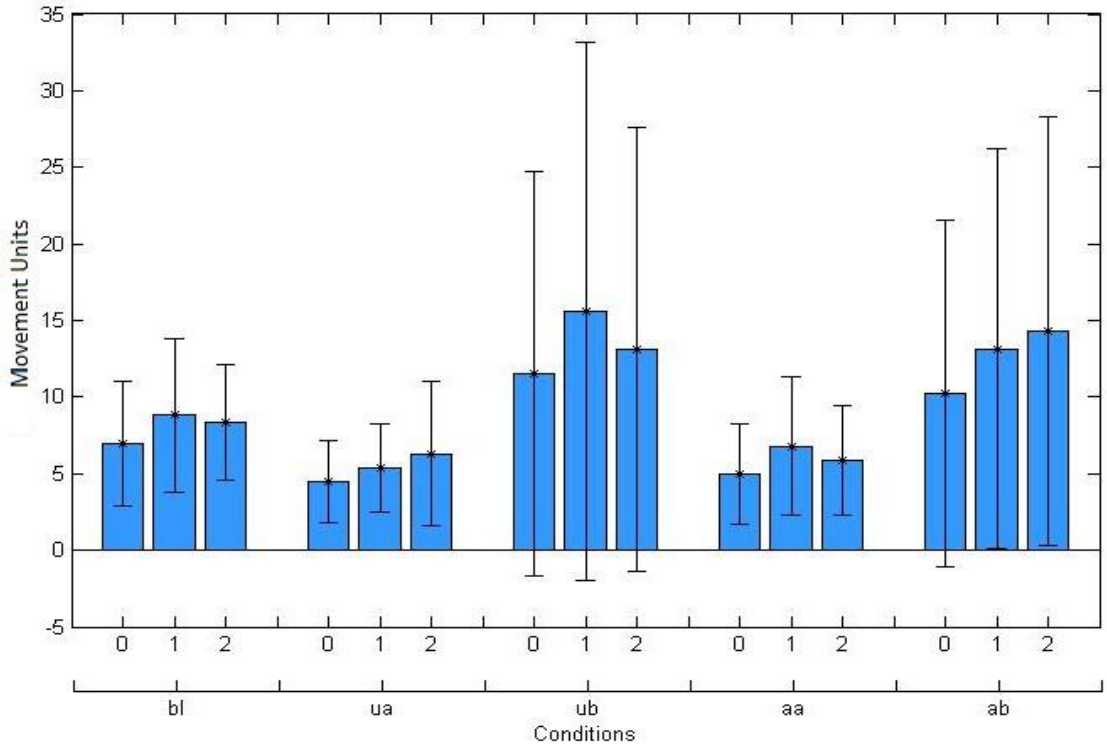

Figure 3.6 Summary of Moment Units for all subjects, each bar represents a target and each cluster represents different condition (bl: baseline; ua: unassisted after; ub: unassisted before; aa: assisted after; ab: assisted before).

Table 3.4 Summary of ANOVA Analysis on Movement Units

ANOVA Table for Movement Units

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	7	834.906	119.272				
Feedback	1	1528.010	1528.010	14.411	.0067	14.411	.910
Feedback * Subject	7	742.240	106.034				
Gravity	1	17.510	17.510	.598	.4648	.598	.101
Gravity * Subject	7	205.073	29.296				
Targets	2	152.063	76.031	6.227	.0116	12.454	.821
Targets * Subject	14	170.938	12.210				
Feedback * Gravity	1	38.760	38.760	.923	.3686	.923	.129
Feedback * Gravity * Subject	7	293.823	41.975				
Feedback * Targets	2	49.146	24.573	2.311	.1357	4.622	.381
Feedback * Targets * Subject	14	148.854	10.632				
Gravity * Targets	2	5.146	2.573	.332	.7230	.664	.092
Gravity * Targets * Subject	14	108.521	7.751				
Feedback * Gravity * Targets	2	6.396	3.198	.338	.7185	.677	.093
Feedback * Gravity * Targets * Subject	14	132.271	9.448				

As can be seen by observing the p-values and power values in Table 3.4 and Figure 3.6, there is a significant and strong effect of Feedback (see also Table 3.5 and Figure 3.7) and of Targets on the number of movement units. Interestingly, there was no effect of Gravity (see also Table 3.6 and Figure 3.8). There is a small interaction effect of feedback by target, but it did not reach the level of significance. With increased number of subjects, this effect might become statistically significant. The interaction effect of Feedback and Gravity did not reach the level of significance (Table 3.7 and Figure 3.9).

Table 3.5 Effects of Feedback on Movement Units

Means Table for Movement Units
Effect: Feedback

	Count	Mean	Std. Dev.	Std. Err.
a	48	5.667	1.950	.281
b	48	13.646	7.617	1.099

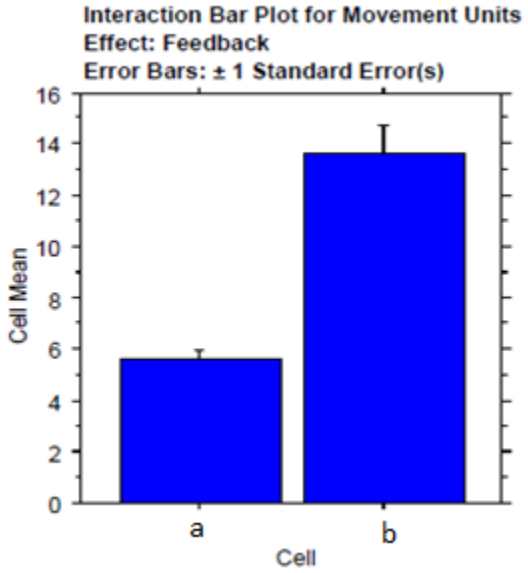

Figure 3.7 Effects of Feedback on Movement Units.

Table 3.6 Effects of Gravity on Movement Units

Means Table for Movement Units
Effect: Gravity

	Count	Mean	Std. Dev.	Std. Err.
u	48	10.083	7.890	1.139
a	48	9.229	5.631	.813

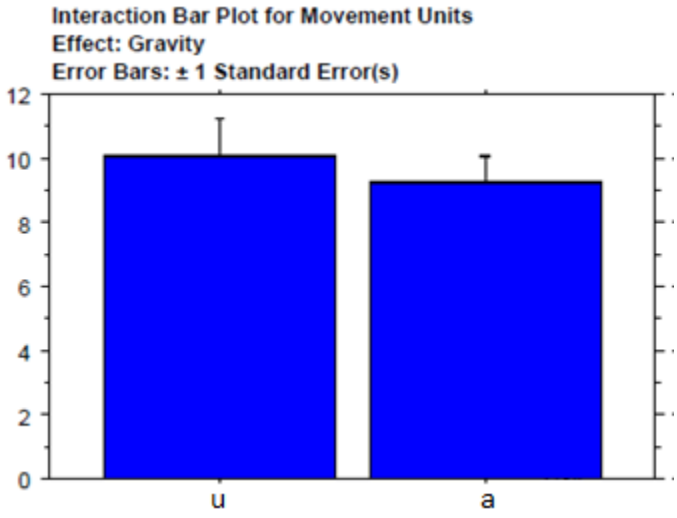

Figure 3.8 Effects of Gravity on Movement Units.

Table 3.7 Effects of Feedback and Gravity on Movement Units

Means Table for Movement Units
Effect: Feedback * Gravity

	Count	Mean	Std. Dev.	Std. Err.
a, u	24	5.458	2.126	.434
a, a	24	5.875	1.777	.363
b, u	24	14.708	8.834	1.803
b, a	24	12.583	6.178	1.261

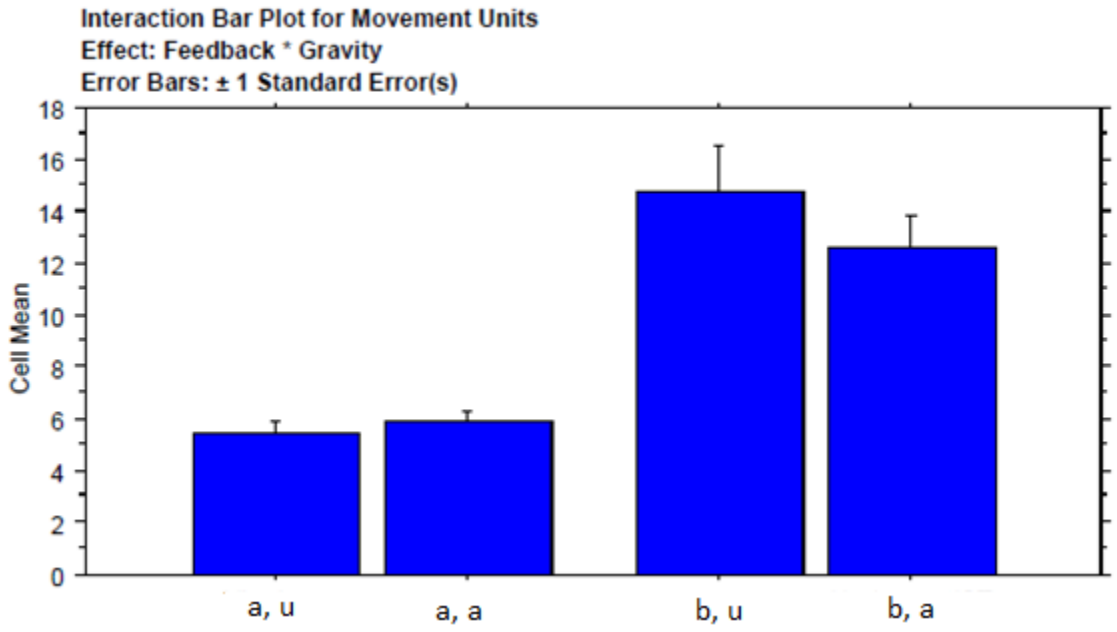

Figure 3.9 Interaction Effect of Feedback by Gravity for Movement Units.

3.3 Time to Peak Velocity

Time to peak velocity is the time from the on-set of the movement to the time when peak velocity is achieved. Figure 3.10 summarizes the observation for the experiment. It can be observed that there is an increasing trend in time to peak velocity from target 0 to target 1 to target 2. It can also be observed, that more time was required to reach peak velocity when the target disappeared before the subject was allowed to move when compared to the conditions when the target disappeared after the subject was allowed to move.

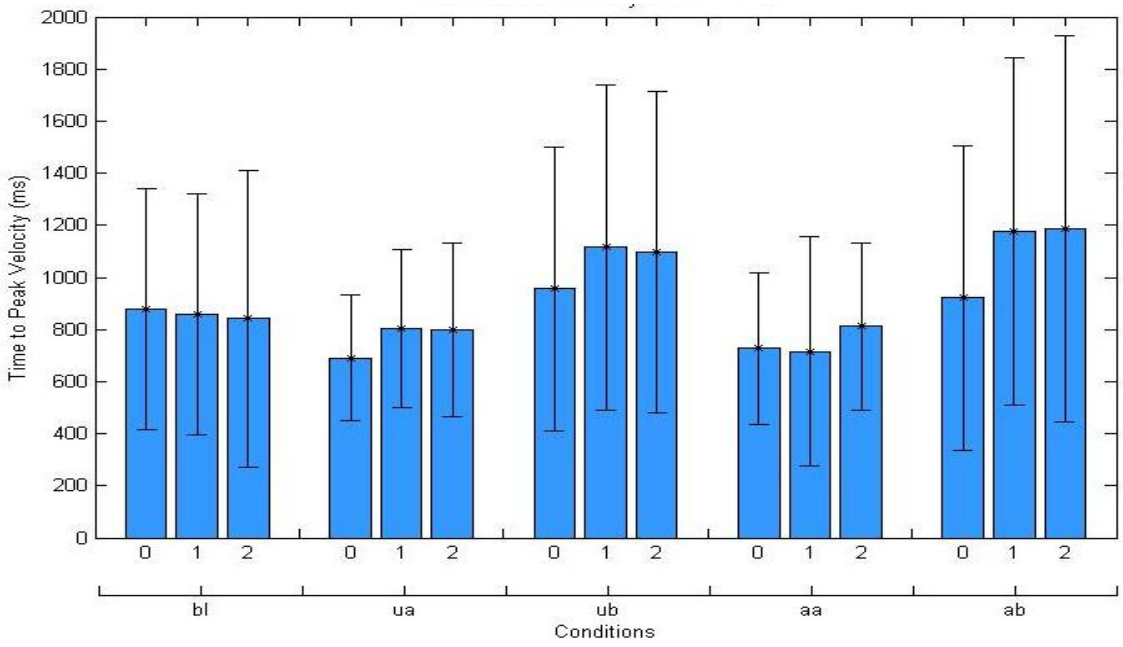

Figure 3.10 Summary of Time to Peak Velocities for all subjects, each bar represents a target and each cluster represents different condition (bl: baseline; ua: unassisted after; ub: unassisted before; aa: assisted after; ab: assisted before).

Table 3.8 Summary of ANOVA Analysis on Time to Peak Velocity

ANOVA Table for Time to Peak Velocity

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	7	4044558.500	577794.071				
Feedback	1	2408376.970	2408376.970	17.934	.0039	17.934	.958
Feedback * Subject	7	940017.196	134288.171				
Gravity	1	3648.200	3648.200	.122	.7373	.122	.060
Gravity * Subject	7	209638.426	29948.347				
Targets	2	417621.932	208810.966	18.077	.0001	36.155	.999
Targets * Subject	14	161714.178	11551.013				
Feedback * Gravity	1	16600.560	16600.560	.417	.5390	.417	.086
Feedback * Gravity * Subject	7	278625.040	39803.577				
Feedback * Targets	2	101664.528	50832.264	2.016	.1700	4.032	.337
Feedback * Targets * Subject	14	352972.666	25212.333				
Gravity * Targets	2	18364.326	9182.163	.398	.6789	.796	.101
Gravity * Targets * Subject	14	322801.617	23057.258				
Feedback * Gravity * Targets	2	50316.391	25158.195	1.508	.2551	3.017	.260
Feedback * Gravity * Targets * Subject	14	233505.349	16678.954				

Table 3.8 shows significant effects of feedback on the time to peak velocity (also shown by Table 3.9 and Figure 3.11). The effects of gravity (also shown by Table 3.10 and Figure 3.12) and interaction effects of feedback by gravity (shown in Table 3.11 and Figure 3.13) are not significant.

Table 3.9 Effect of Feedback on Time to Peak Velocity

Means Table for Time to Peak Velocity
Effect: Feedback

	Count	Mean	Std. Dev.	Std. Err.
a	48	758.260	200.576	28.951
b	48	1075.040	334.575	48.292

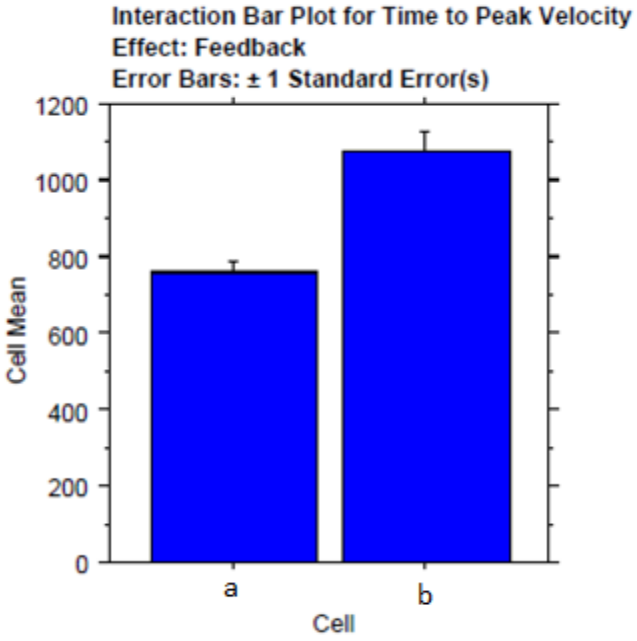

Figure 3.11 Effect of Feedback on Time to Peak Velocity.

Table 3.10 Effect of Gravity on Time to Peak Velocity

Means Table for Time to Peak Velocity
Effect: Gravity

	Count	Mean	Std. Dev.	Std. Err.
u	48	910.485	313.691	45.277
a	48	922.815	323.935	46.756

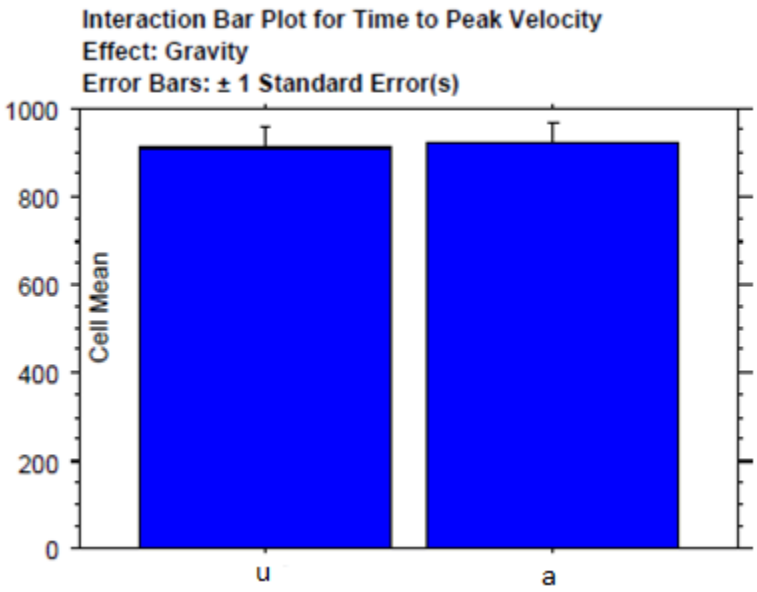

Figure 3.12 Effect of Gravity on Time to Peak Velocity.

Table 3.11 Effect of Feedback and Gravity on Time to Peak Velocity

Means Table for Time to Peak Velocity
Effect: Feedback * Gravity

	Count	Mean	Std. Dev.	Std. Err.
a, u	24	765.246	199.102	40.641
a, a	24	751.275	206.076	42.065
b, u	24	1055.725	342.662	69.946
b, a	24	1094.354	332.494	67.870

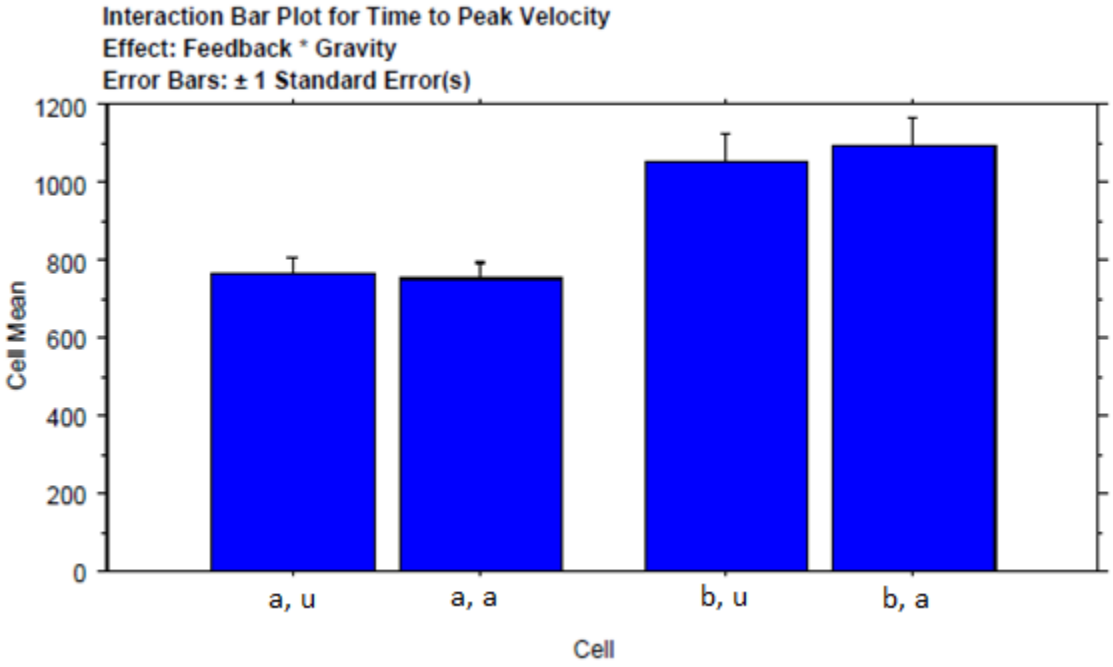

Figure 3.13 Interaction Effect of Feedback by Gravity on Time to Peak Velocity.

3.4 Time after Peak Velocity

Time after peak velocity is the time required from the time when peak velocity is achieved to the movement off-set. The following graph shows the group mean data for time after peak velocity. It can be observed that the time after peak velocity in the baseline condition is higher as compared to all the other conditions. Also, it can be

observed, by comparing Figures 3.14 and 3.10 that more time is required to reach the target after peak velocity than to reach peak velocity after movement on-set.

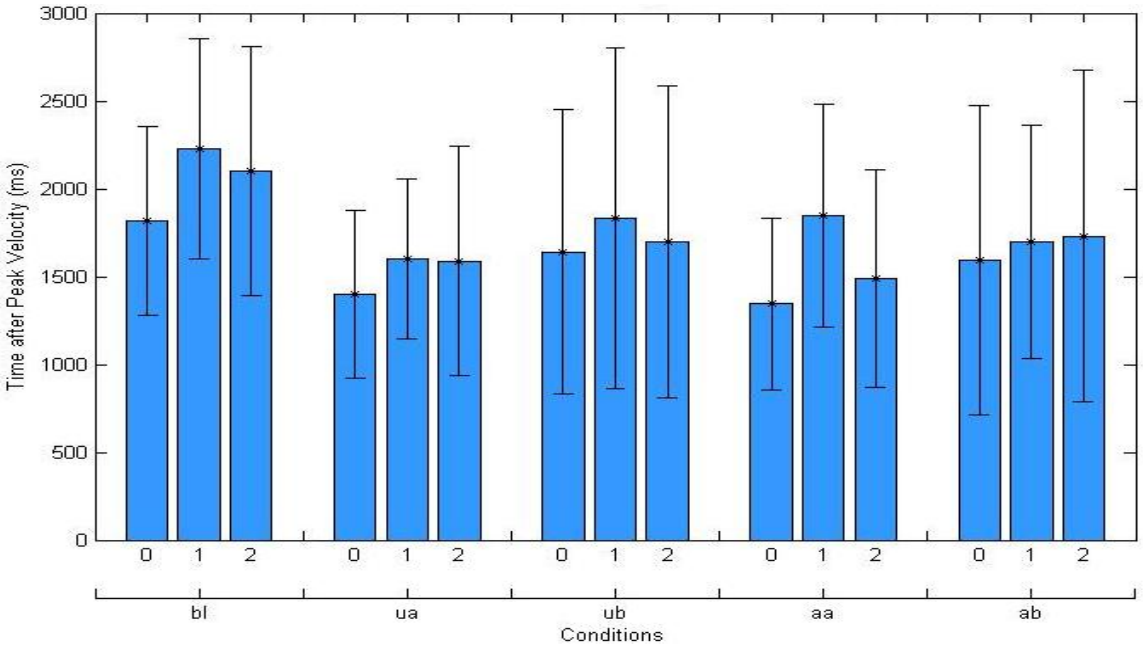

Figure 3.14 Summary of Time after Peak Velocities for all subjects, each bar represents a target and each cluster represents different condition (bl: baseline; ua: unassisted after; ub: unassisted before; aa: assisted after; ab: assisted before).

Table 3.12 Summary of ANOVA Analysis on Time after Peak Velocity

ANOVA Table for Time after Velocity

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	7	1611224.884	230174.983				
Feedback	1	566492.190	566492.190	2.663	.1467	2.663	.283
Feedback * Subject	7	1488846.426	212692.347				
Gravity	1	1753.605	1753.605	.021	.8878	.021	.052
Gravity * Subject	7	573145.751	81877.964				
Targets	2	1005385.375	502692.688	6.826	.0085	13.653	.858
Targets * Subject	14	1030942.008	73638.715				
Feedback * Gravity	1	38837.238	38837.238	.170	.6921	.170	.065
Feedback * Gravity * Subject	7	1595436.632	227919.519				
Feedback * Targets	2	170925.576	85462.788	2.383	.1287	4.765	.392
Feedback * Targets * Subject	14	502194.650	35871.046				
Gravity * Targets	2	51100.454	25550.227	.583	.5711	1.166	.125
Gravity * Targets * Subject	14	613341.763	43810.126				
Feedback * Gravity * Targets	2	280414.560	140207.280	2.374	.1295	4.748	.391
Feedback * Gravity * Targets * Subject	14	826880.053	59062.861				

Table 3.12 and Figure 3.14 show no effect of feedback on time after peak velocity (see also Table 3.13 and Figure 3.15). The same is true for the effects of gravity (Table 3.14 and Figure 3.16) and for the interaction effect of feedback by gravity (Table 3.15 and Figure 3.17).

Table 3.13 Effect of Feedback on Time after Peak Velocity

Means Table for Time after Velocity
Effect: Feedback

	Count	Mean	Std. Dev.	Std. Err.
a	48	1545.356	339.210	48.961
b	48	1698.992	305.358	44.075

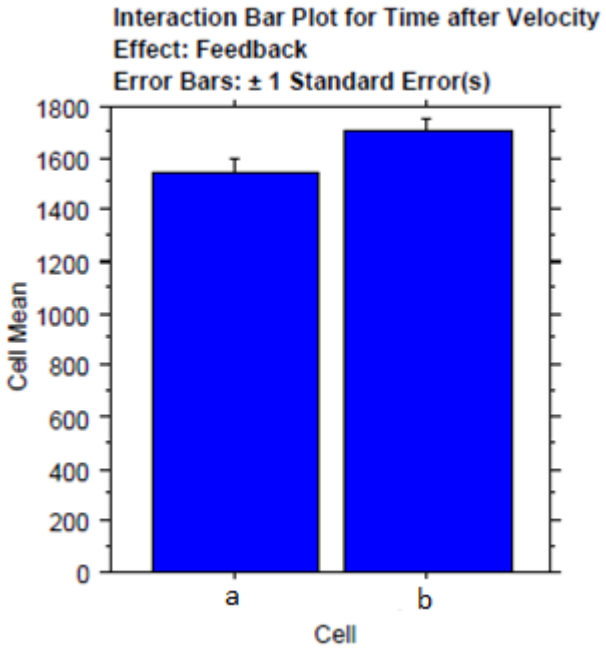

Figure 3.15 Effect of Feedback on Time after Peak Velocity.

Table 3.14 Effect of Gravity on Time after Peak Velocity

Means Table for Time after Velocity
Effect: Gravity

	Count	Mean	Std. Dev.	Std. Err.
u	48	1626.448	345.424	49.858
a	48	1617.900	317.812	45.872

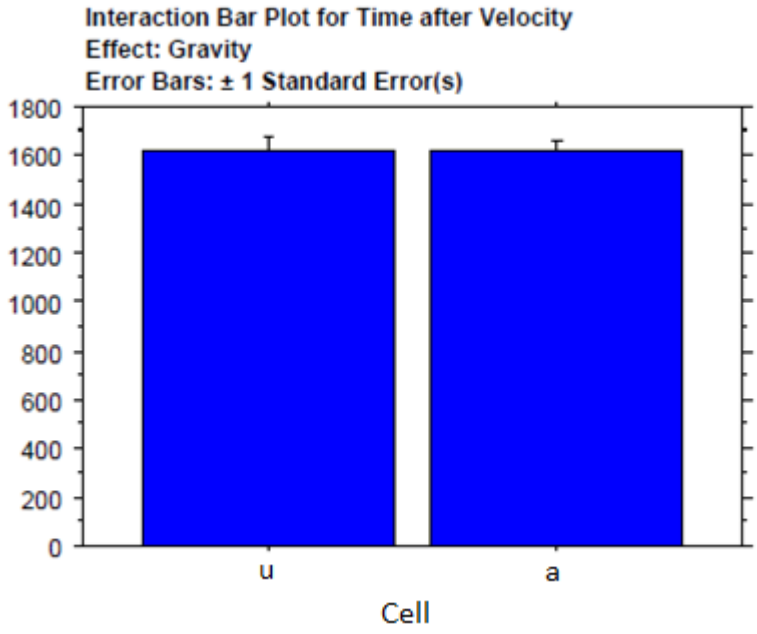

Figure 3.16 Effect of Gravity on Time after Peak Velocity.

Table 3.15 Effect of Feedback and Gravity on Time after Peak Velocity

Means Table for Time after Velocity
Effect: Feedback * Gravity

	Count	Mean	Std. Dev.	Std. Err.
a, u	24	1529.517	349.311	71.303
a, a	24	1561.196	335.542	68.492
b, u	24	1723.379	319.683	65.255
b, a	24	1674.604	295.131	60.243

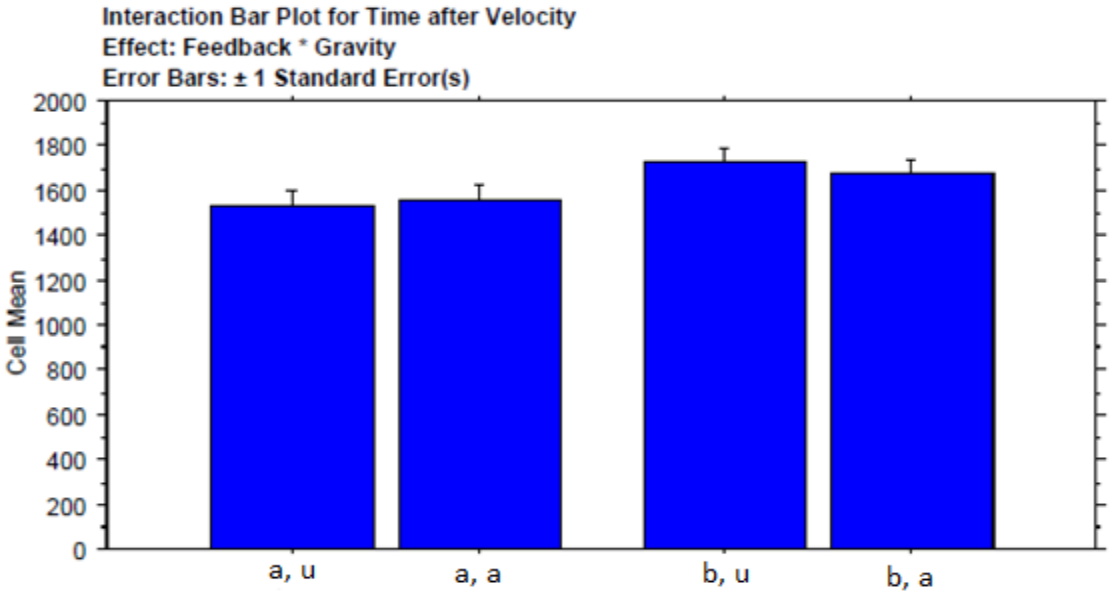

Figure 3.17 Interaction Effect of Feedback by Gravity on Time after Peak Velocity.

3.5 3D Position Error

3D position error is defined as the root squared difference between the average X, Y and Z coordinates of the arm endpoint at the time of movement reversal in the baseline, bl condition (perceived target location) and the X, Y and Z coordinates of the arm endpoint position at the time of movement reversal in a given trial in the experimental conditions. Figure 3.18 gives the summary of 3D position errors for the experiment. It can be observed that the subjects made larger errors in before conditions (ub and ab) as

compared to after conditions (ua and aa). Also, it can be observed that the subjects made more errors in target 1 as compared to target 0 and 2.

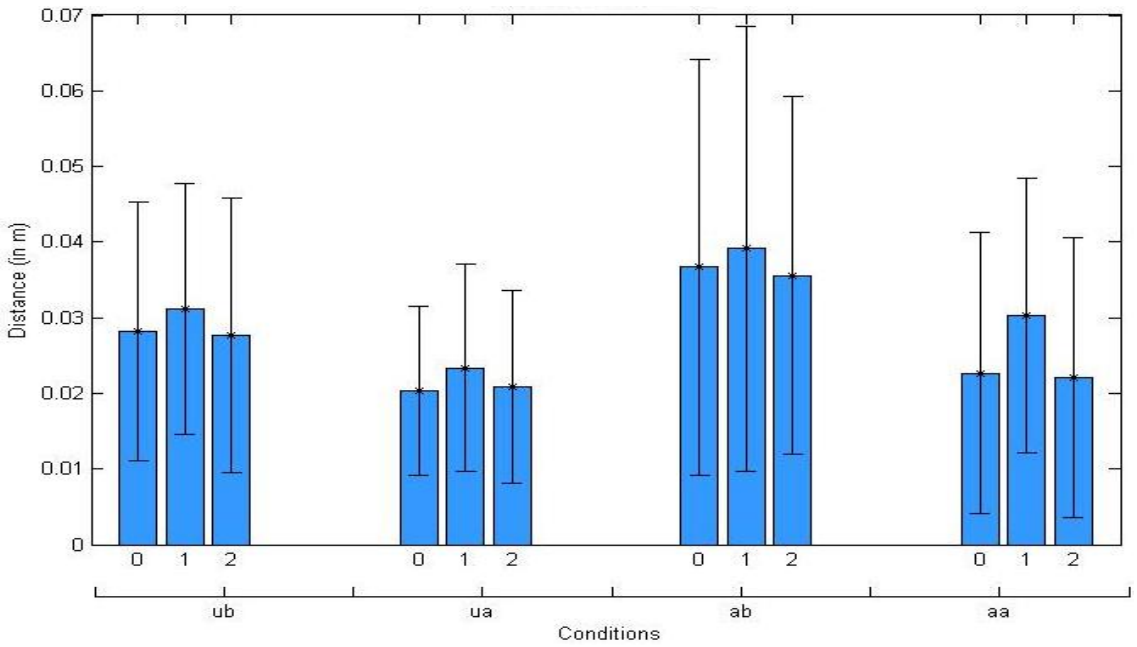

Figure 3.18 Summary of 3D Position Errors for all subjects, each bar represents the mean error for a target and each group represents different condition (bl: baseline; ua: unassisted after; ub: unassisted before; aa: assisted after; ab: assisted before). Standard Deviations are marked by the error bars.

3.6 X, Y and Z Position Error

X, y and z position errors are the difference in coordinate values between average position of the target perceived in baseline condition and average position of the target perceived in the other conditions in each of the X, Y and Z directions. Figures 3.19, 3.23 and 3.27 are the experimental observations for the X, Y and Z position errors. The positive distance represents overshooting and the negative sign stands for the undershooting of the target when compared to the target position in baseline condition. It

can be observed that there were more errors in before conditions as compared to the after conditions.

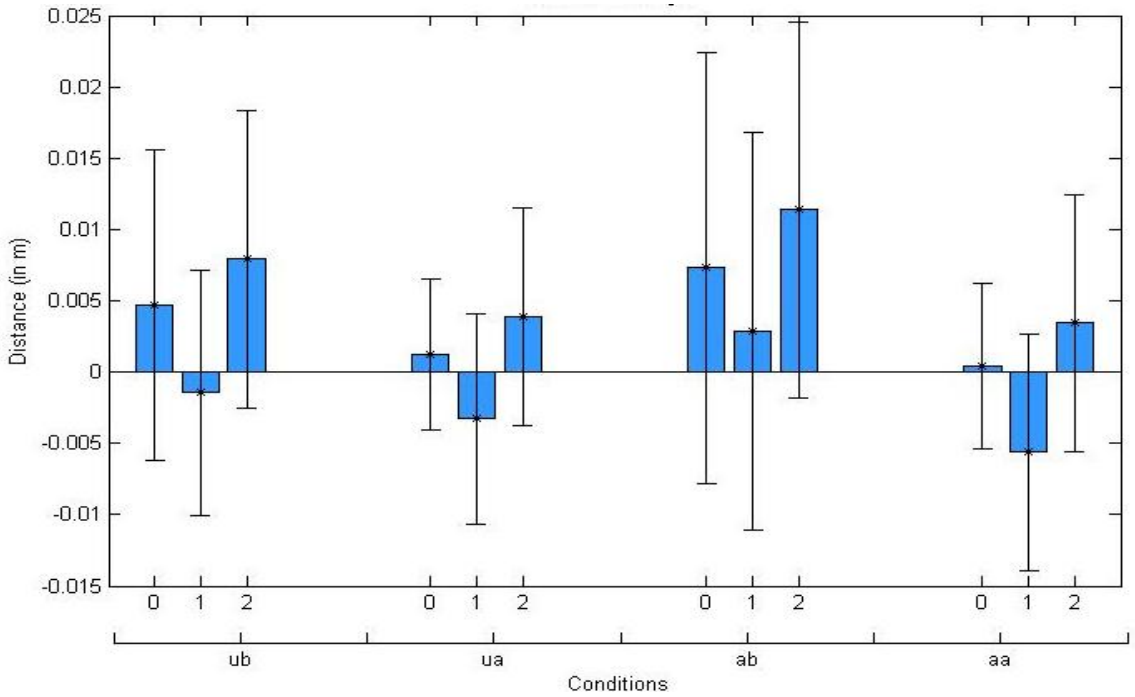

Figure 3.19 Summary of X Position Errors for all subjects, each bar represents the mean error for a target and each cluster represents different condition (bl: baseline; ua: unassisted after; ub: unassisted before; aa: assisted after; ab: assisted before). Standard Deviations are marked by the error bars.

Table 3.16 Summary of ANOVA Analysis of X-Position Error

ANOVA Table for X Error

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	7	.003	4.445E-4				
Vision	1	.001	.001	3.820	.0916	3.820	.384
Vision * Subject	7	.001	1.844E-4				
Gravity	1	2.766E-5	2.766E-5	.467	.5162	.467	.090
Gravity * Subject	7	4.142E-4	5.917E-5				
Target	2	.001	.001	8.421	.0040	16.843	.926
Target * Subject	14	.001	6.889E-5				
Vision * Gravity	1	1.248E-4	1.248E-4	3.029	.1253	3.029	.316
Vision * Gravity * Subject	7	2.884E-4	4.120E-5				
Vision * Target	2	3.181E-6	1.591E-6	.062	.9403	.124	.058
Vision * Target * Subject	14	3.604E-4	2.574E-5				
Gravity * Target	2	1.943E-6	9.713E-7	.108	.8984	.216	.063
Gravity * Target * Subject	14	1.260E-4	8.998E-6				
Vision * Gravity * Target	2	1.165E-5	5.824E-6	.861	.4440	1.722	.164
Vision * Gravity * Target * Subject	14	9.471E-5	6.765E-6				

As shown in the Table 3.19 and Figures 3.22; there is a small effect of Feedback (Vision) and Gravity on the X-Position error but they did not reach the level of significance. The effect of Feedback as shown by the p-value in Table 3.16 (see also 3.17 and Figure 3.20) is close to significant. The high standard deviation values reduce the significance in the differences in the errors across conditions. With increased number of subjects the differences might become statistically significant.

Table 3.17 Effect of Feedback on X-Position Error

Means Table for X Error
Effect: Vision

	Count	Mean	Std. Dev.	Std. Err.
a	48	3.431E-5	.007	.001
b	48	.005	.011	.002

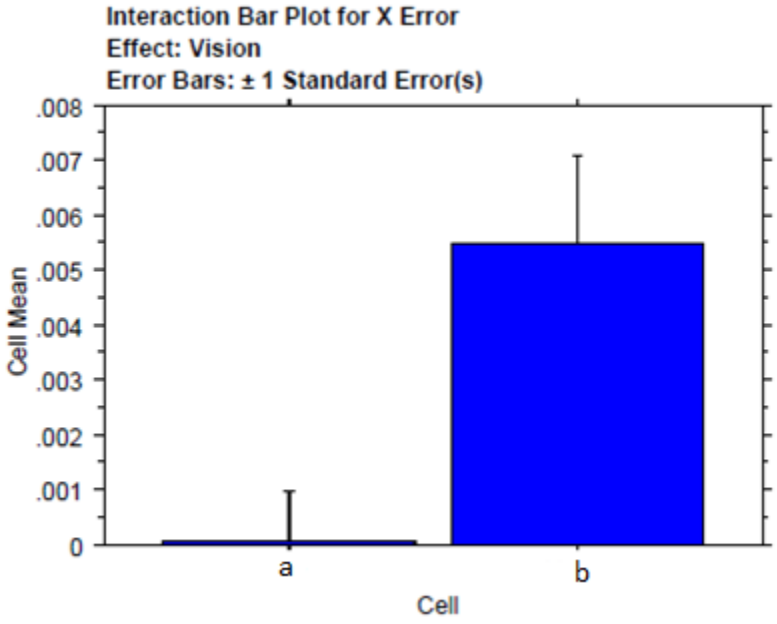

Figure 3.20 Effect of Feedback on X-Position Error.

Table 3.18 Effect of Gravity on X-Position Error

Means Table for X Error
Effect: Gravity

	Count	Mean	Std. Dev.	Std. Err.
u	48	.002	.008	.001
a	48	.003	.011	.002

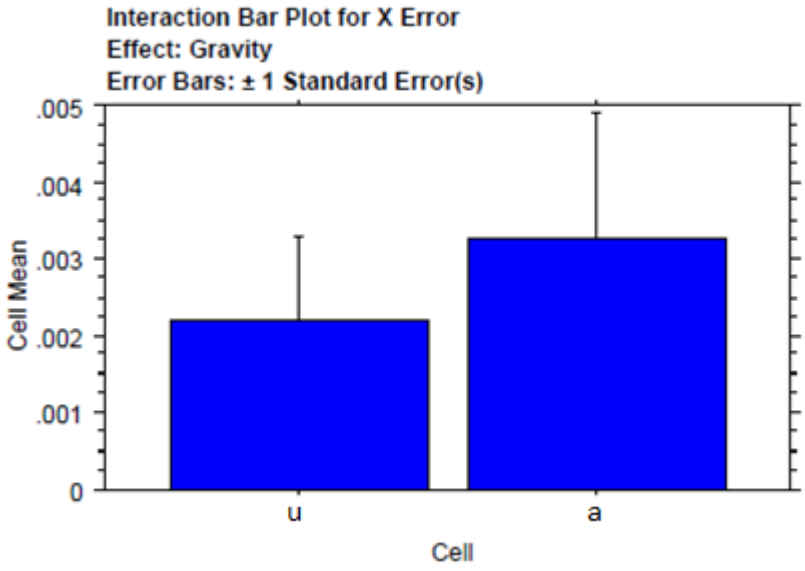

Figure 3.21 Effect of Gravity on X-Position Error.

Table 3.19 Effect of Feedback and Gravity on X- Position Error

	Count	Mean	Std. Dev.	Std. Err.
a, u	24	.001	.006	.001
a, a	24	-.001	.007	.001
b, u	24	.004	.009	.002
b, a	24	.007	.013	.003

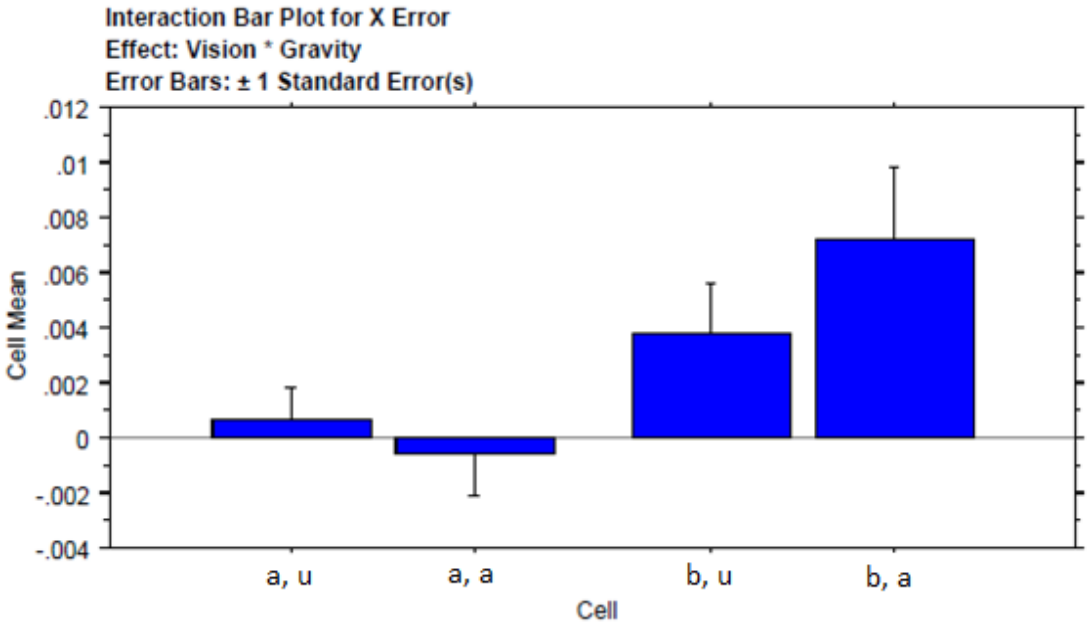

Figure 3.22 Effects of Feedback and Gravity on X-Position Error.

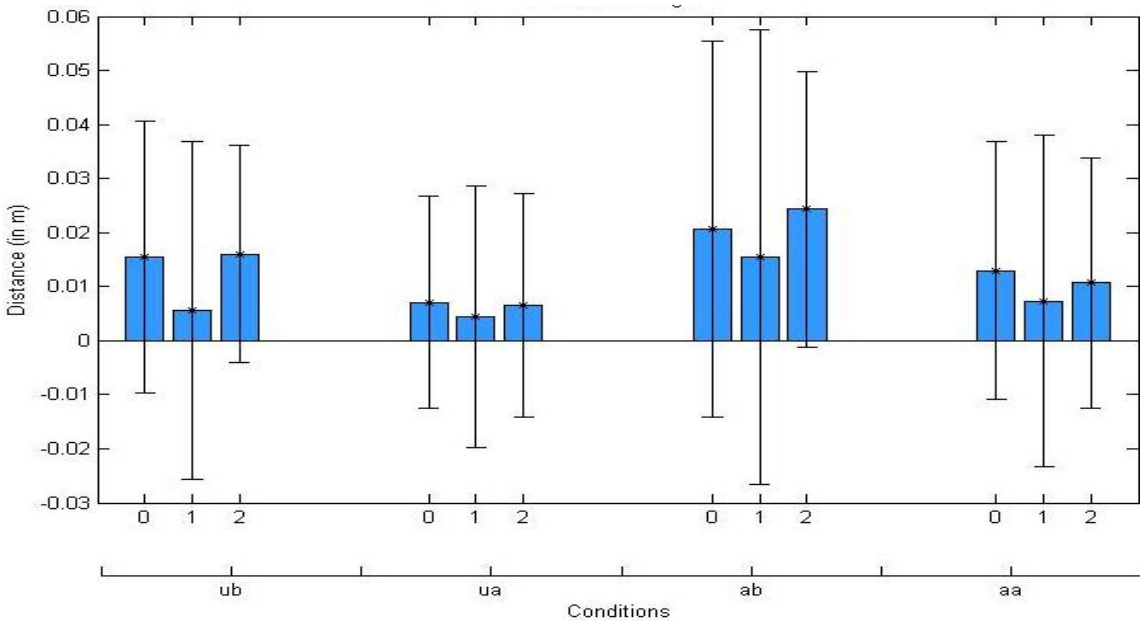

Figure 3.23 Summary of Y Position Errors for all subjects, each bar represents the mean error for a target and each cluster represents different condition (bl: baseline; ua: unassisted after; ub: unassisted before; aa: assisted after; ab: assisted before). Standard Deviations are marked by the error bars.

Table 3.20 Summary of ANOVA Analysis of Y-Position Error

ANOVA Table for Y Error

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	7	.040	.006				
Vision	1	.002	.002	2.340	.1699	2.340	.254
Vision * Subject	7	.005	.001				
Gravity	1	.001	.001	1.946	.2057	1.946	.219
Gravity * Subject	7	.003	4.400E-4				
Target	2	.001	4.149E-4	1.050	.3758	2.101	.192
Target * Subject	14	.006	3.950E-4				
Vision * Gravity	1	7.109E-5	7.109E-5	.260	.6260	.260	.072
Vision * Gravity * Subject	7	.002	2.737E-4				
Vision * Target	2	1.884E-4	9.419E-5	2.287	.1382	4.574	.378
Vision * Target * Subject	14	.001	4.118E-5				
Gravity * Target	2	4.115E-6	2.058E-6	.077	.9262	.154	.059
Gravity * Target * Subject	14	3.737E-4	2.670E-5				
Vision * Gravity * Target	2	6.405E-5	3.203E-5	3.649	.0530	7.297	.569
Vision * Gravity * Target * Subject	14	1.229E-4	8.777E-6				

As shown in the Table 3.20 (see also Tables 3.21, 3.22 and 3.23 and Figures 3.23, 3.24, 3.25 and 3.26); there is a small effect of Feedback (Vision) and Gravity on the Y-Position error but they are not significant. The high standard deviation reduces the significance in differences in the Y errors. With increased number of subjects some of these differences might become statistically significantly.

Table 3.21 Effect of Feedback on Y-Position Error

Means Table for Y Error
Effect: Vision

	Count	Mean	Std. Dev.	Std. Err.
a	48	.008	.020	.003
b	48	.016	.029	.004

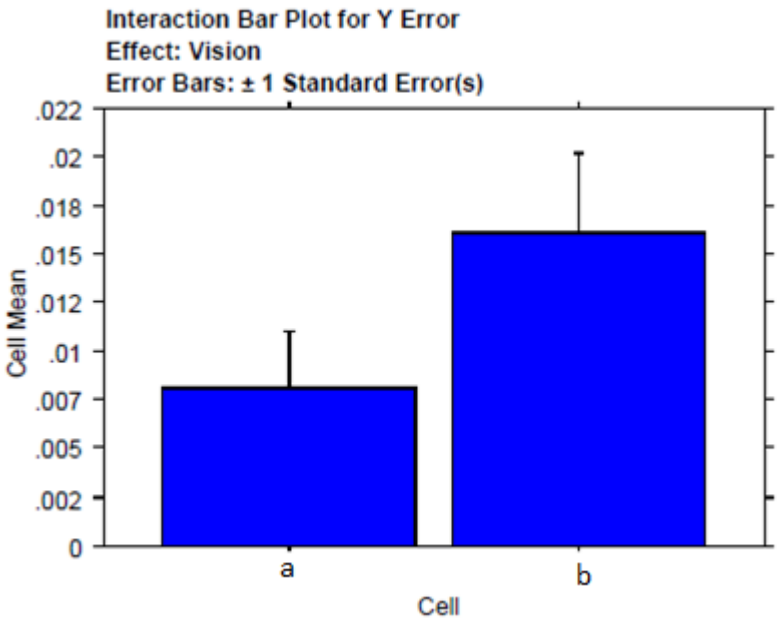

Figure 3.24 Effect of Feedback on Y-Position Error.

Table 3.22 Effect of Gravity on Y-Position Error

Means Table for Y Error
Effect: Gravity

	Count	Mean	Std. Dev.	Std. Err.
u	48	.009	.021	.003
a	48	.015	.029	.004

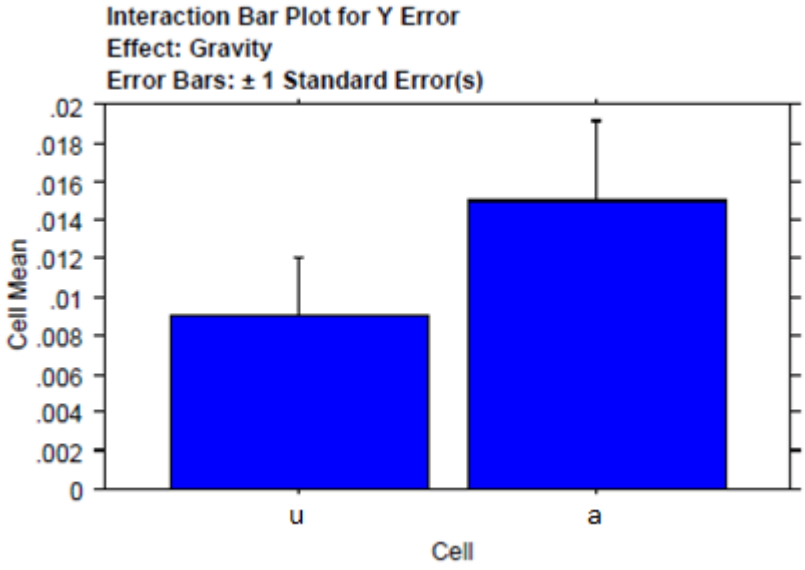

Figure 3.25 Effect of Gravity on Y-Position Error.

Table 3.23 Effect of Feedback and Gravity on Y- Position Error

	Count	Mean	Std. Dev.	Std. Err.
a, u	24	.006	.017	.003
a, a	24	.010	.023	.005
b, u	24	.012	.024	.005
b, a	24	.020	.033	.007

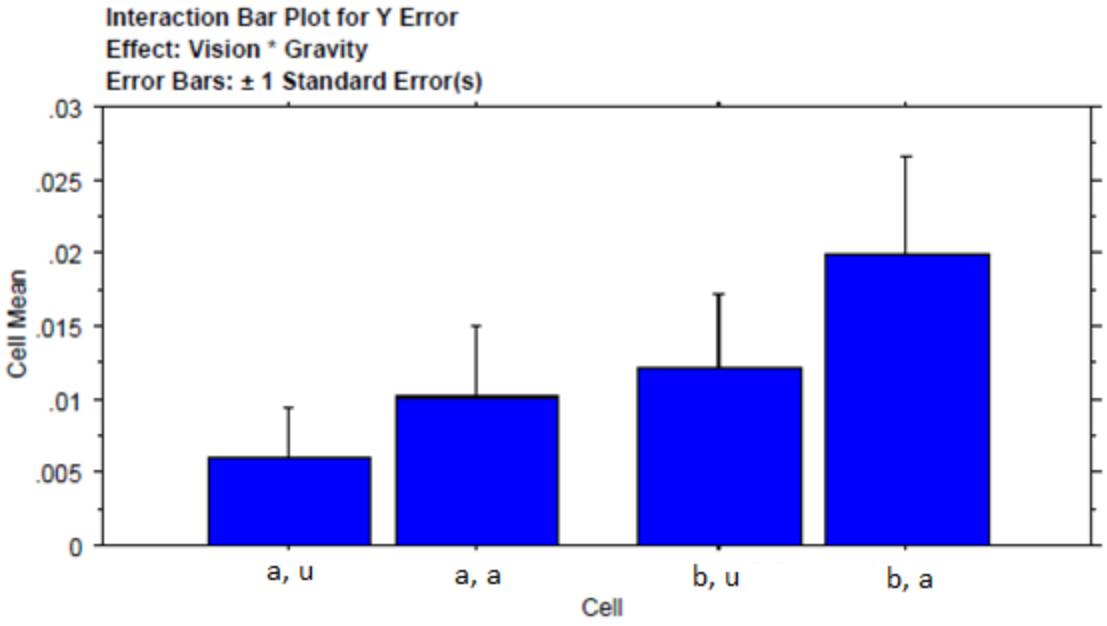

Figure 3.26 Effect of Feedback and Gravity on Y-Position Error.

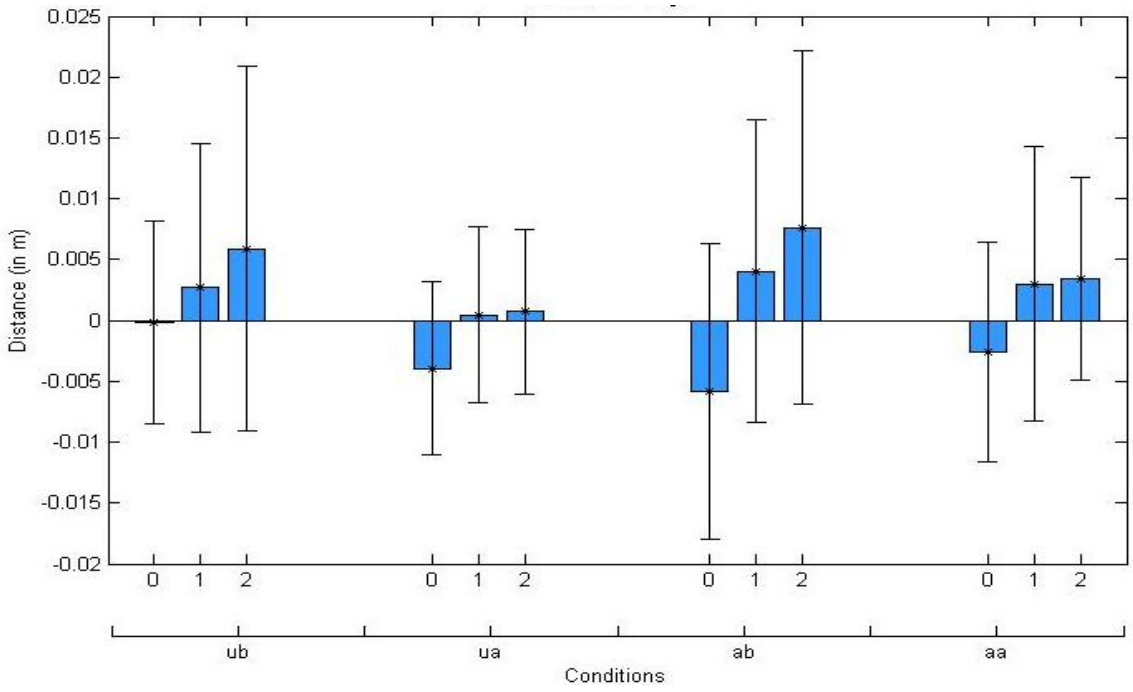

Figure 3.27 Summary of Z Position Errors for all subjects, each bar represents the mean error for a target and each cluster represents different condition (bl: baseline; ua: unassisted after; ub: unassisted before; aa: assisted after; ab: assisted before). Standard Deviations are marked by the error bars.

Table 3.24 Summary of ANOVA Analysis of Z-Position Error

ANOVA Table for Z Error

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	7	.003	3.717E-4				
Vision	1	1.105E-4	1.105E-4	1.582	.2488	1.582	.187
Vision * Subject	7	4.891E-4	6.987E-5				
Gravity	1	9.641E-6	9.641E-6	.279	.6136	.279	.074
Gravity * Subject	7	2.418E-4	3.455E-5				
Target	2	.001	4.965E-4	6.615	.0095	13.229	.845
Target * Subject	14	.001	7.507E-5				
Vision * Gravity	1	5.581E-5	5.581E-5	3.802	.0922	3.802	.383
Vision * Gravity * Subject	7	1.028E-4	1.468E-5				
Vision * Target	2	7.601E-5	3.800E-5	1.725	.2140	3.449	.293
Vision * Target * Subject	14	3.085E-4	2.203E-5				
Gravity * Target	2	9.788E-5	4.894E-5	2.694	.1023	5.389	.438
Gravity * Target * Subject	14	2.543E-4	1.816E-5				
Vision * Gravity * Target	2	4.780E-5	2.390E-5	3.284	.0677	6.568	.521
Vision * Gravity * Target * Subject	14	1.019E-4	7.278E-6				

As shown in the Table 3.24 (see also Tables 3.25, 3.26 and 3.27) and Figure 3.27 (see also Figures 3.28, 3.29 and 3.30); there is a small effect of Feedback (Vision) and Feedback (Vision) by Gravity on the Z-Position error but it is not significant. The high standard deviation reduces the significance in differences in the Z errors. With increased number of subjects the differences might be statistically significantly.

Table 3.25 Effect of Feedback on Z-Position Error

Means Table for Z Error
Effect: Vision

	Count	Mean	Std. Dev.	Std. Err.
a	48	9.431E-5	.006	.001
b	48	.002	.010	.001

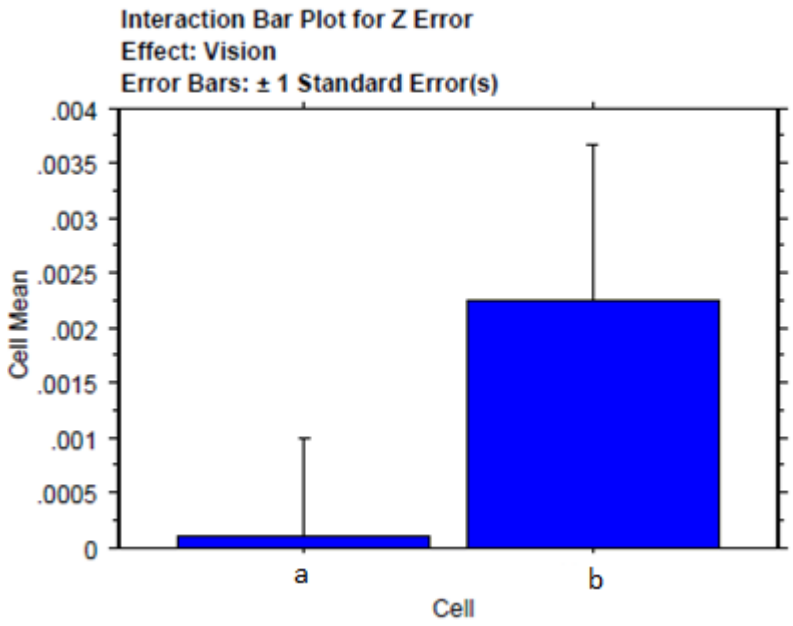

Figure 3.28 Effect of Feedback on Z-Position Error.

Table 3.26 Effect of Gravity on Z-Position Error

Means Table for Z Error
Effect: Gravity

	Count	Mean	Std. Dev.	Std. Err.
u	48	.001	.008	.001
a	48	.001	.009	.001

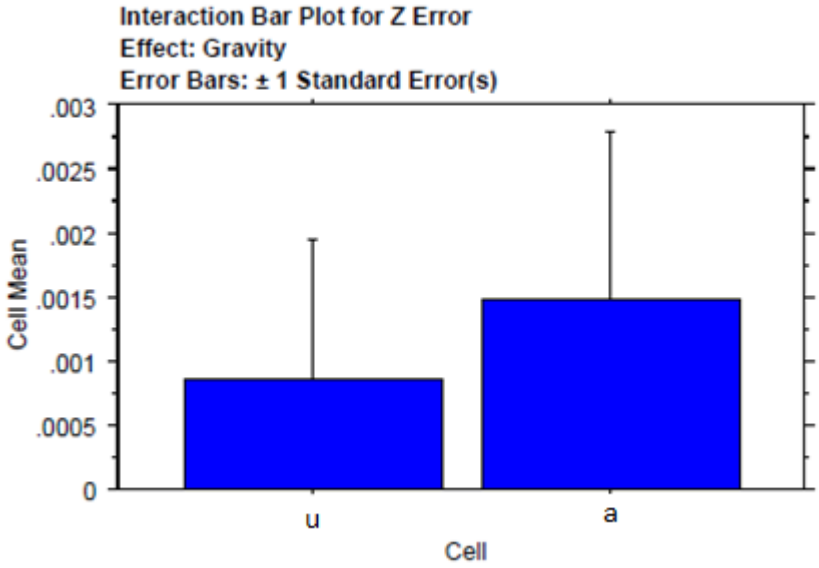

Figure 3.29 Effect of Gravity on Z-Position Error.

Table 3.27 Effect of Feedback and Gravity on Z- Position Error

	Count	Mean	Std. Dev.	Std. Err.
a, u	24	-.001	.005	.001
a, a	24	.001	.007	.001
b, u	24	.003	.009	.002
b, a	24	.002	.011	.002

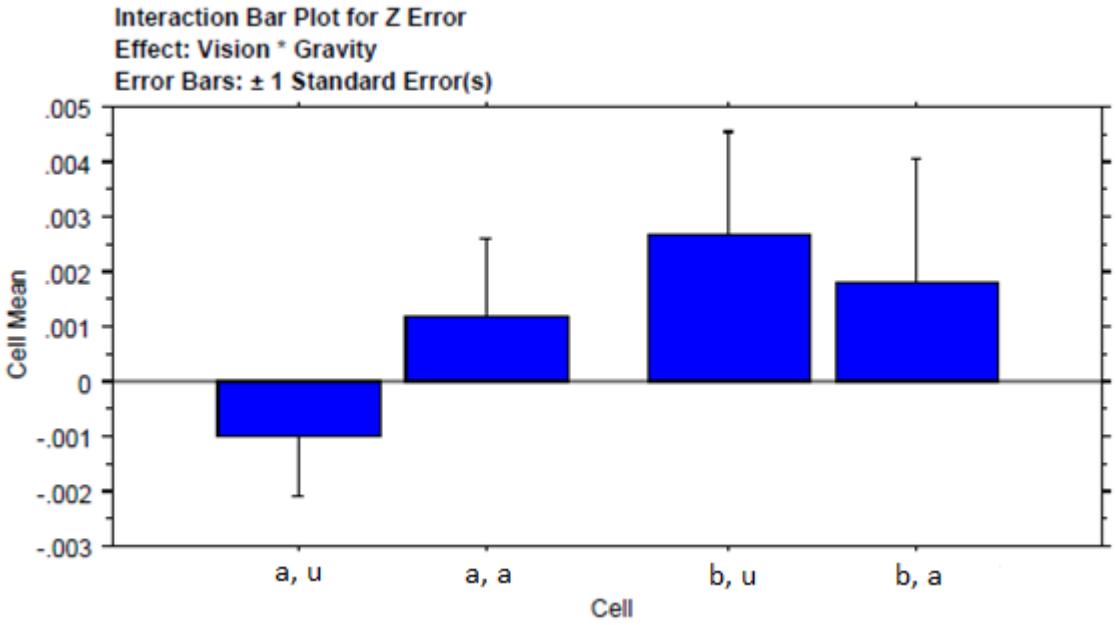

Figure 3.30 Effects of Feedback and Gravity on Z-Position Error.

3.7 Elevation Error

Elevation error is defined as an angle between the following two vectors. First vector is formed by the average starting position (average is calculated across all conditions) and average target position as it is perceived in bl (baseline) condition. The second vector is formed by the average starting position (average is calculated across all conditions) and the average target position perceived in the other conditions. It is calculated by taking the dot product of the two vectors, dividing it by the product of amplitudes of the two vectors and then taking the arc cosine of the result. Figure 3.31 summarizes the experimental

observations for the elevation errors. It can be observed that the subjects made more elevation errors in before conditions as compared to after conditions.

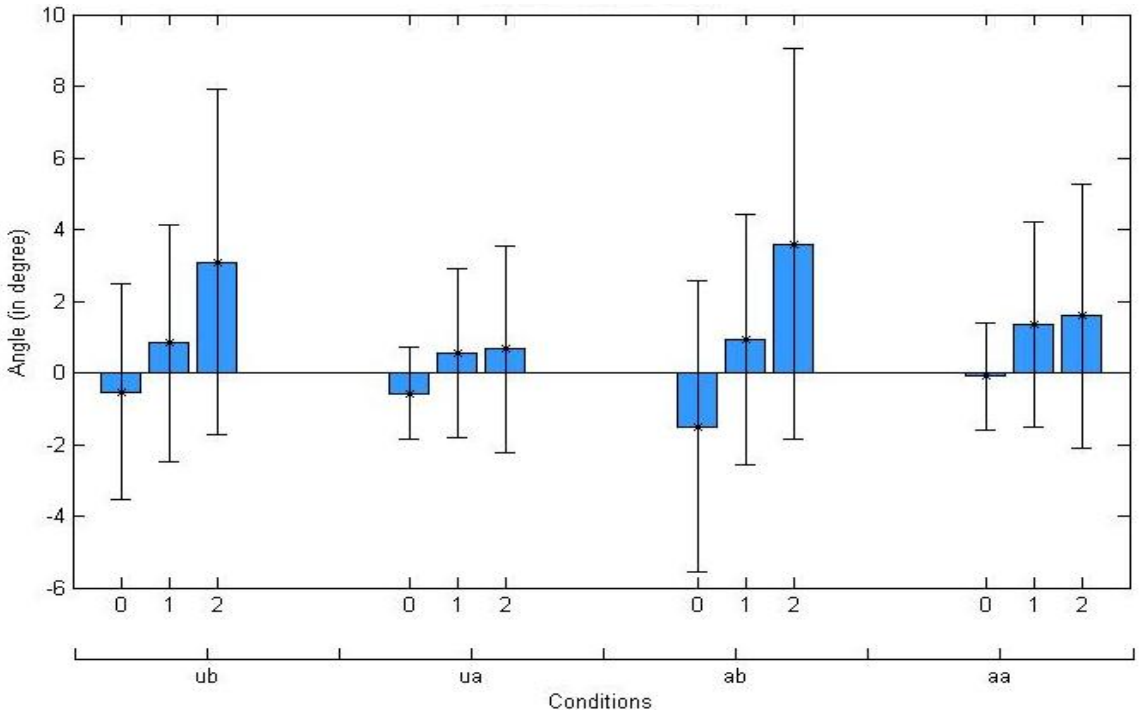

Figure 3.31 Summary of Elevation Errors all subjects, each bar represents the mean error for a target and each cluster represents different condition (bl: baseline; ua: unassisted after; ub: unassisted before; aa: assisted after; ab: assisted before). Standard Deviations are marked by the error bars.

Table 3.28 Summary of ANOVA Analysis on Elevation Error

ANOVA Table for Elev Error

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	7	182.993	26.142				
Vision	1	5.149	5.149	.557	.4798	.557	.097
Vision * Subject	7	64.702	9.243				
Gravity	1	2.269	2.269	.807	.3988	.807	.119
Gravity * Subject	7	19.671	2.810				
Target	2	134.016	67.008	8.068	.0047	16.135	.914
Target * Subject	14	116.280	8.306				
Vision * Gravity	1	4.280	4.280	1.020	.3463	1.020	.137
Vision * Gravity * Subject	7	29.385	4.198				
Vision * Target	2	36.288	18.144	5.405	.0182	10.809	.758
Vision * Target * Subject	14	47.000	3.357				
Gravity * Target	2	3.756	1.878	1.094	.3620	2.187	.198
Gravity * Target * Subject	14	24.044	1.717				
Vision * Gravity * Target	2	1.083	.542	.311	.7375	.622	.089
Vision * Gravity * Target * Subject	14	24.367	1.740				

As shown in Table 3.28 (see also Table 3.29, 3.30 and 3.31) and Figure 3.31 (see also Figure 3.32, 3.33 and 3.34); there is a significant Feedback (Vision) by Target interaction effect on the elevation error. The Feedback (Vision) and Gravity effects were not significant. The high standard deviation reduces the significance in differences in the elevation errors.

Table 3.29 Effect of Feedback on Elevation Errors

Means Table for Elev Error
Effect: Vision

	Count	Mean	Std. Dev.	Std. Err.
a	48	.563	1.804	.260
b	48	1.026	3.381	.488

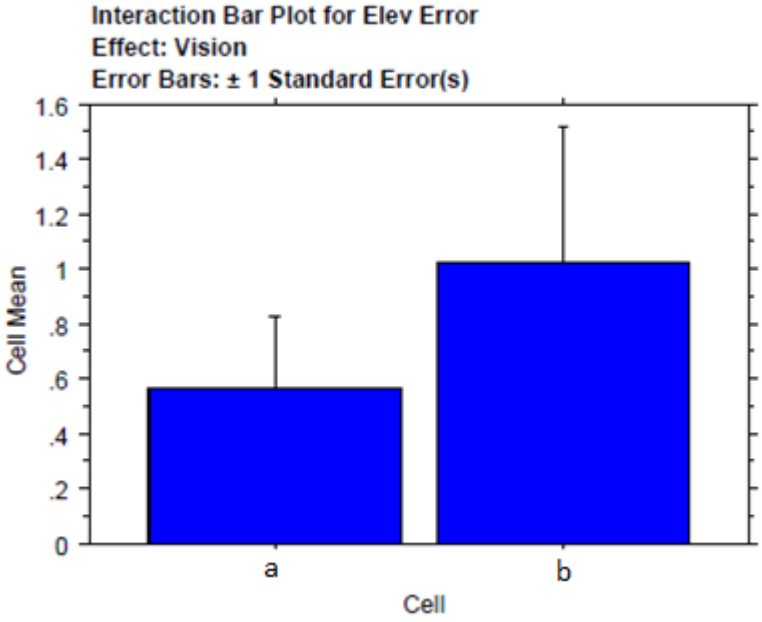

Figure 3.32 Effect of Feedback on Elevation Error.

Table 3.30 Effect of Gravity on Elevation Errors

Means Table for Elev Error
Effect: Gravity

	Count	Mean	Std. Dev.	Std. Err.
u	48	.641	2.312	.334
a	48	.948	3.066	.442

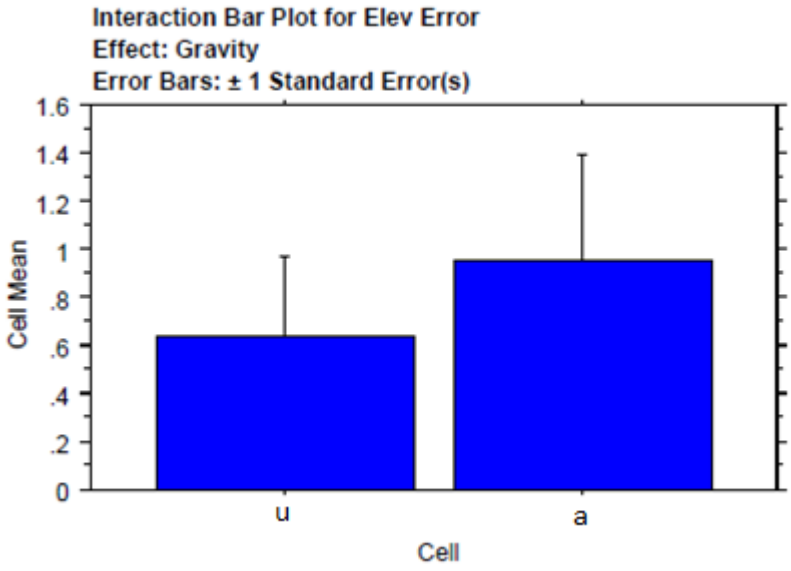

Figure 3.33 Effect of Gravity on Elevation Error.

Table 3.31 Effect of Feedback and Gravity on Elevation Error

Means Table for Elev Error
Effect: Vision * Gravity

	Count	Mean	Std. Dev.	Std. Err.
a, u	24	.198	1.490	.304
a, a	24	.928	2.037	.416
b, u	24	1.083	2.880	.588
b, a	24	.969	3.880	.792

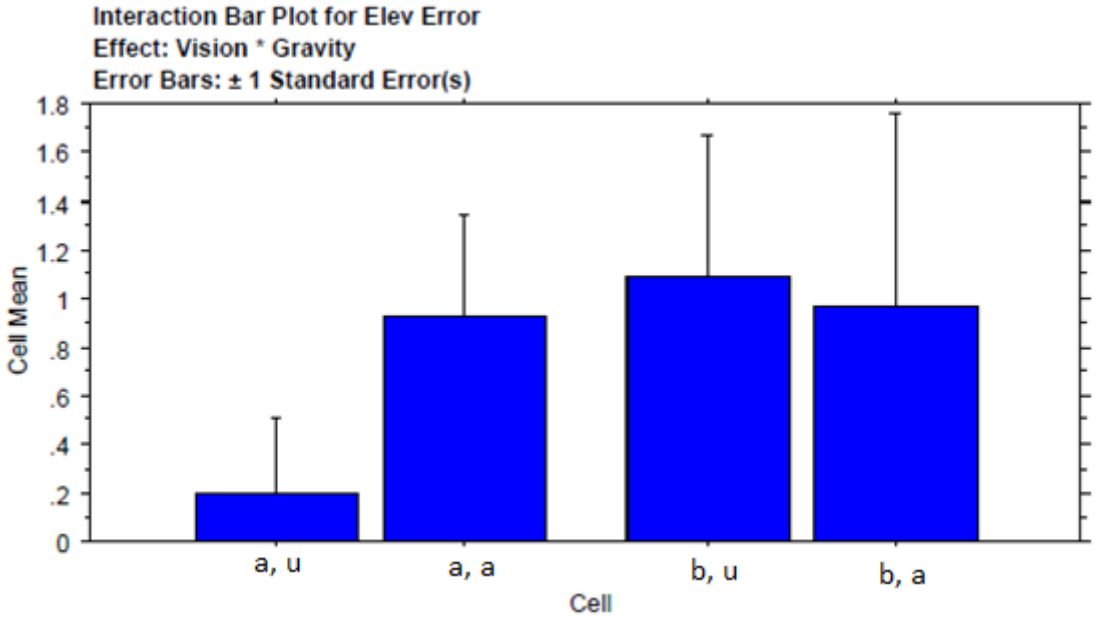

Figure 3.34 Effects of Feedback and Gravity on Elevation Error.

3.8 3D Angle Error

3D angle error is defined as the angle between the vectors formed between average starting position to average target position perceived in bl condition and average starting position to average target position perceived in the other conditions. It is calculated by taking the dot product of the two vectors, dividing it by the product of amplitudes of the

two vectors and then taking the arc cosine of the result. Figure 3.35 summarizes the experimental observations for the 3D angle errors. It can be observed that the subjects made more 3D angle errors in before conditions as compared to after conditions. It can also be observed that the subjects made more 3D angle errors for target 1 as compared to target 0 and 2.

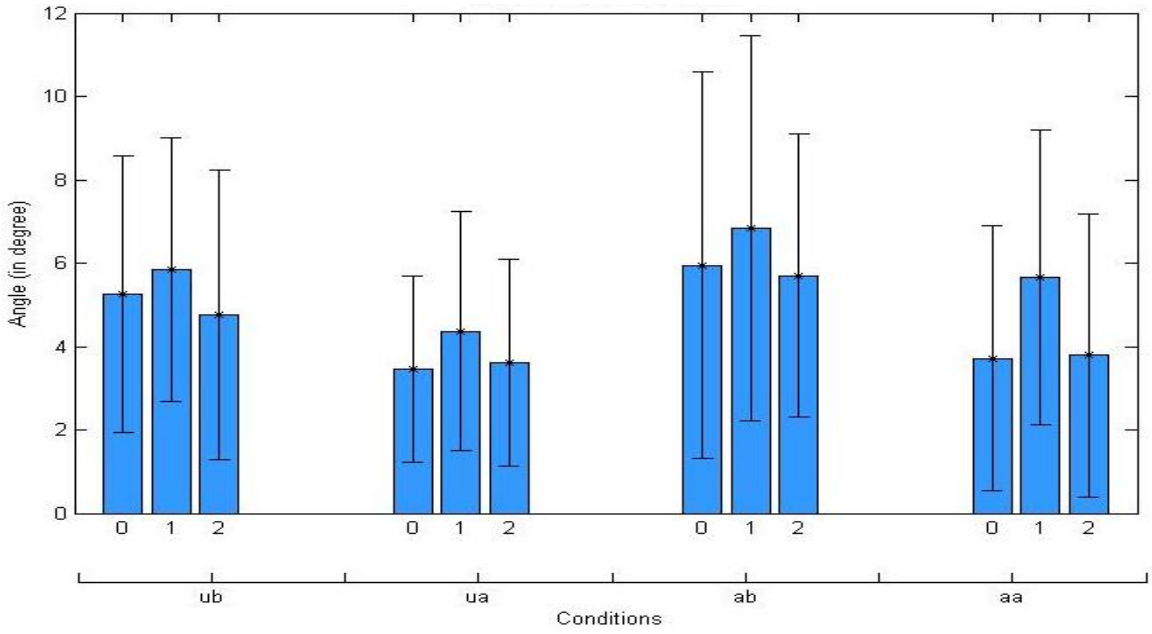

Figure 3.35 Summary of 3D Angle Errors for all subjects, each bar represents the mean error for a target and each cluster represents different condition (bl: baseline; ua: unassisted after; ub: unassisted before; aa: assisted after; ab: assisted before). Standard Deviations are marked by the error bars.

3.9 Radial Error

Radial error is defined as the vector difference between the vectors formed between average starting position to average target position perceived in bl condition and average starting position to average target position perceived in the other conditions. The negative sign indicates that subjects undershoot in all the condition as compared to the baseline condition. In Figure 3.36, it can be seen that the radial errors are higher in before conditions as compared to after conditions.

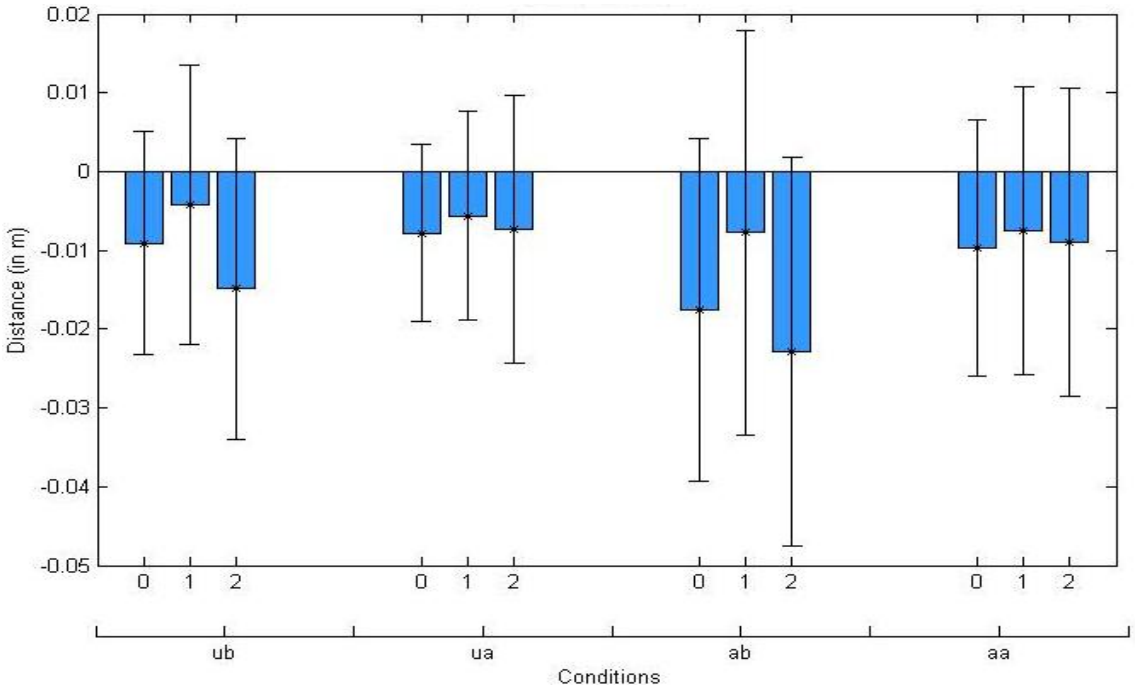

Figure 3.36 Summary of Radial Errors for all subjects, each bar represents the mean error for a target and each cluster represents different condition (bl: baseline; ua: unassisted after; ub: unassisted before; aa: assisted after; ab: assisted before). Standard Deviations are marked by the error bars.

CHAPTER 4

DISCUSSION

This chapter concludes the thesis by discussing the results and the statistical analysis. It discusses the possible reasons that might have lead to the observed results over the expected results.

This thesis was oriented towards finding significant differences in the reach action performed by healthy humans if there was a variation in the environment in which they performed the movement. It was expected to observe significant differences in the errors due to the effect of vision (or feedback), i.e., the target disappears before or after the subject is allowed to move, and the effect of gravity, i.e., movement assisted or unassisted. The differences could have been due to the effects of vision and gravity independently or to the interaction of the two.

As shown in Sections 3.1, moving from target 0 to target 1 to target 2, there is a decrease in peak velocity. Also, the 3D position errors and 3D angle errors are higher for target 1 as compared to target 0 and 2. The possible reasoning for this is the position of targets on screen. As shown in Figure 2.7, target 0 is on the center left of the display, target 1 on top center and target 2 at the bottom right of the display. The starting point reference stand was below the screen level in height at the centre of x axis of the display. All of the eight subjects were right handed and the pointer attached to the HM was on the right side of their seating position. The height of target 1 was largest, and then was target 0 and the closest was target 2 to the starting point reference stand. The variation in errors can be accounted for by the variation in heights of the targets from the starting point.

As shown in the statistical analysis there are effects of vision or gravity on the parameters of movement kinematics and pointing errors, but they were not found to be significant. The primary cause of these observations can be attributed to high standard deviations and low power of the test, which in turn is the result of less number of subjects. If the number of subjects were increased, significant differences could be observed.

REFERENCES

Adamovich, S.V., Berkinblit, M.B., Fookson, O., & Poizner, H. (1998). Pointing in 3D space toremembered targets: I. Kinesthetic versus visual target presentation. *Journal of Neurophysiology*, 79: 2833-2846.

Berkinblit, M.B., Fookson, O.I., Smetanin, B., Adamovich, S.V. & Poizner, H. (1995). The interaction of visual and proprioceptive inputs in pointing to actual and remembered targets. *Exp.Brain Res.,* 107: 326-330.

Beurze, S.M., Van Pelt, S. & Medendrop, W.P. (2006). Behavioral Reference Frames for Planning Human Reach Movements. *Journal of Neurophysiology,* 97: 352-362.

Bourgeois, J. & Coello, Y. (2009). Role of Inertial Properties of the Upper Limb on the Perception of the Boundary of Peripersonal Space. *Psychologie Francaise*, 54: 225-239.

Darling, W.G. & Miller, G.F. (1993). Transformations between visual and kinesthetic coordinate system in reaches to remembered object locations and orientations. *Exp.Brain Res.*, 93: 534-547.

Izawa, J., Rane, T., Donchin, O. & Shadmehr, R.(2008). Motor Adaptation as a Process of Reoptimization. *Journal of Neurophysiology*, 28: 2883-2891.

Vindras, P., Desmurget, M., Prablanc, C. & Viviani, P. (1998). Pointing Errors Reflect Biases in the Perception of the Initial Hand Position. *Journal of Neurophysiology*, 76: 3290-3294.

Soechting, J.F. and Flanders, M. (1989a). Sensorimotor representations for pointing to targets in three-dimensional space. *Journal of Neurophysiology*, 62: 582-594.

Soechting, J.F. and Flanders, M. (1989b). Errors in pointing are due to approximations in sensorimotor transformations. *Journal of Neurophysiology*, 62: 595-608.

Messier, J. & Kalaska, J.F. (1999). Comparison of Variability of Initial Kinematics and Endpoints of Reaching Movements. *Exp.Brain Res.* 125: 139-152.

Morasso, P. (1981). Spatial Control of Arm Movements. *Exp.Brain Res.* 42: 223-227.

Poizner, H., Wooten, E., & Salot, D. (1986) Computergraphic modeling and analysis: a portable system for tracking arm movements in three-dimensional space. *Behav. Res. Methods Instruments Computers*, 18: 427-433.