Case Western Reserve University

The Ocular Motor System

A Quantitative Evaluation

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EBME 318: Biomedical Engineering Laboratory I

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***Abstract*— Quantitative infrared oculographic evaluation of horizontal pursuit can be used to study the different neural mechanisms responsible for control of the eyes. The mere fact that "the eye may be quicker than vision" insinuates the necessity for a computer-aided capturing system. Ultimately, target pursuit became less and less accurate for each subject as target velocity increased –i.e. target velocity in smooth pursuit as well as target jumping amplitudes in saccadic pursuit.**

I. Introduction

If I were to add an introduction, it would appear here…

II. Methods

Using a collection of equipment including computer-based high-speed digital video eye tracker, rotating chair with head stabilization, laser aimed at a 2-D mirror galvanometer system, amplifiers, and the LabVIEW data acquisition system, we conducted a series of tests of the ocular motor subsystems described in the introduction. These test were performed with two subjects across four experiments:

Experiment I. Smooth pursuit performance.

Experiment II. Visual gain and ocular motor control.

Experiment III. Saccadic performance.

Experiment IV. Vestibular-ocular reflex performance and control.

III. Results

See discussion section…

IV. DISCUSSION

Following from the raw lab results provided in the previous section, this section will explore the significance of these results in the context of the experiment, through the guiding questions outlined for us:

Question 1.

The first four trials tested the eye's ability to maintain a smooth pursuit. For this, we used velocity parameters of 5°, 10°, 20°, and 40°/sec for the trapezoidal waveform target trajectories. Since, according to our data, the subject's left eye is consistently closer in alignment with the target, let us single out the left eye for these analyses.

By definition, the smooth pursuit gain, G, is the ratio of eye velocity to target velocity. To perform this calculation, it was necessary to zoom in on very small windows of time in the recorded data to capture unbiased samples of the subject's eye velocity –i.e. without saccadic interruptions.

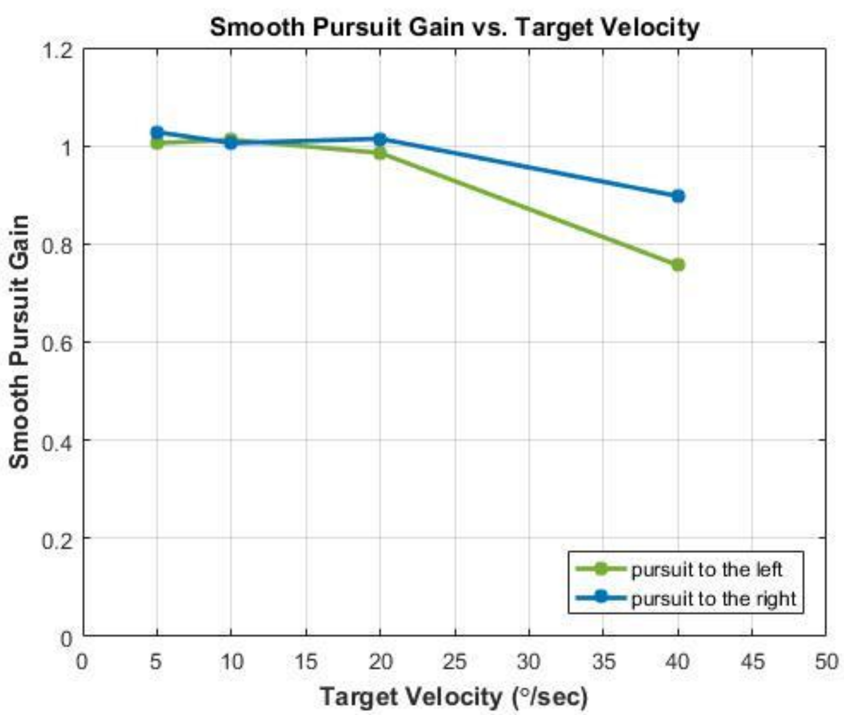

Fig. 1. *Horizontal smooth pursuit gain (eye velocity/target velocity) versus the four constant target velocities: 5°, 10°, 20°, and 40°/sec. Eye velocities were extracted from brief time windows in Trials 1-4, over the course of which the subject's ability to maintain accurate smooth pursuit of linear trajectories (constituent of an overall trapezoidal waveform trajectory) became significantly more difficult as target velocity was increased.*

Coincidentally, the Fig. 1 in Sharpe & Sylvester's study, published in 1978, shows normal data expected for young as well as elderly subjects. When compared to their results, averaging from the fifteen young subjects used in their study, our results—as shown in *our* Fig. 1 and from only one subject—are very close in alignment with the expected results. The only noteworthy discrepancy occurs between the gains obtained at 40°/sec, and it can be almost entirely attributed to the fact that eye trajectory slopes were measured in separate time frames of each trial. Naturally, this introduced high amounts of variability throughout the set of velocity samples. Ideally, given more time, I could have collected a handful of eye velocity samples, then averaged them to realize a more normalized representation of smooth pursuit gain.

Question 2.

Just like with linear trajectories, the pursuit gain of sinusoidal trajectories can be found by taking samples near the zero crossing, where velocity reaches a peak. With peak target amplitudes of ±15° and frequencies of 0.05, 0.1, 0.5, and 1.0 hertz, as well as peak target velocities consistent with Question 1, each trial yielded clean enough results to establish a reliable smooth pursuit gain from a single sample.

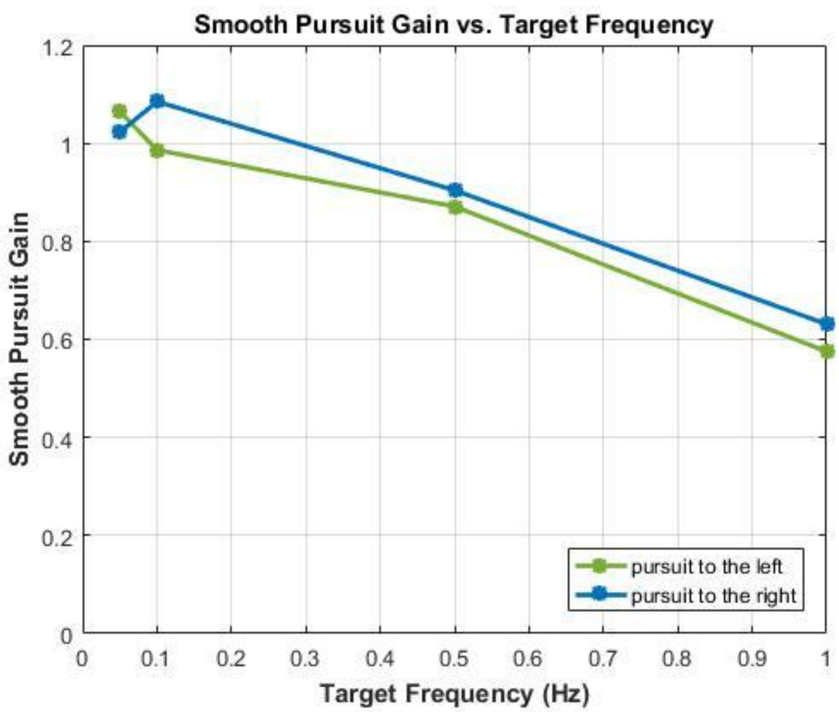

Fig. 2. *Horizontal smooth pursuit gain (eye velocity/target velocity) versus the four constant target frequencies: 0.05 Hz, 0.1 Hz, 0.5 Hz, and 1.0 Hz. These gains were calculated using samples taken from narrow time frames in Trials 5-8, surrounding the zero crossing of the target trajectory, where the peak velocity was achieved. The decrease in ability to maintain smooth pursuit is even more apparent here than it is in Fig. 1.*

When assessing the differences between results from sinusoidal pursuit versus linear pursuit, it is clear that the subject had greater difficulty anticipating and following sinusoidal target trajectories. For instance, where the smooth pursuit gains at a target velocity of 20°/sec for Trial 3 (in Fig. 1) are just around 1.0, the gains obtained by the third trial of sinusoidal pursuit (i.e. Trial 7) can be seen (in Fig. 2) to be noticeably lower, and then even lower by the last trial, conducted at 1.0 Hz.

Next, for the same set of trials, the phase lag (or lead) of eye velocity relative to target velocity and its change with target frequency are shown in

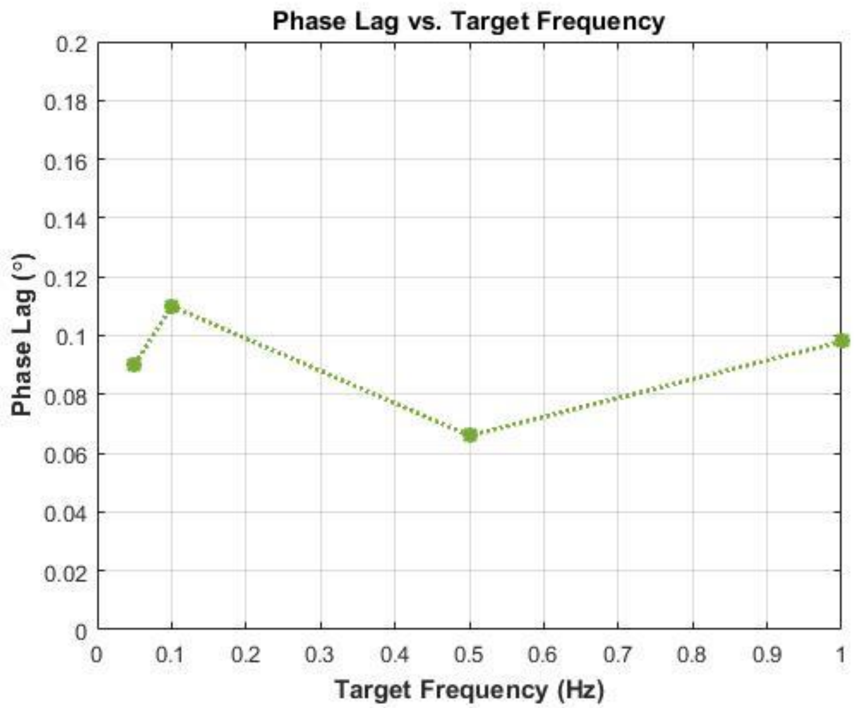

Fig. 3. *Horizontal phase lag (of eye position with respect to target position) versus the four constant target frequencies: 0.05 Hz, 0.1 Hz, 0.5 Hz, and 1.0 Hz. These delays were measured using samples taken from narrow time frames in Trials 5-8, using the zero crossing as a reference point on both the target trajectory and the eye trajectory. (Note: once again, this measurement concerns only the subject's left eye.)*

At low frequencies, the tracking was primarily *pursuit*, and it became more and more *saccadic* towards the higher frequencies. Judging by these characteristics, it appears that the frequency response of the system would initially be more sporadic if it was measured using less-predictable target motion. That said, I believe the overall response would become more homogenous as more measurements were to be made. In effect, randomizing the target's motion would most likely produce results that do not depend as much on the independent variable here.

Question 3.

For the two attempts at pursuit in the dark, after the experiment, the subject *did* think that he made smooth movements. Fig. 4 illustrates this:

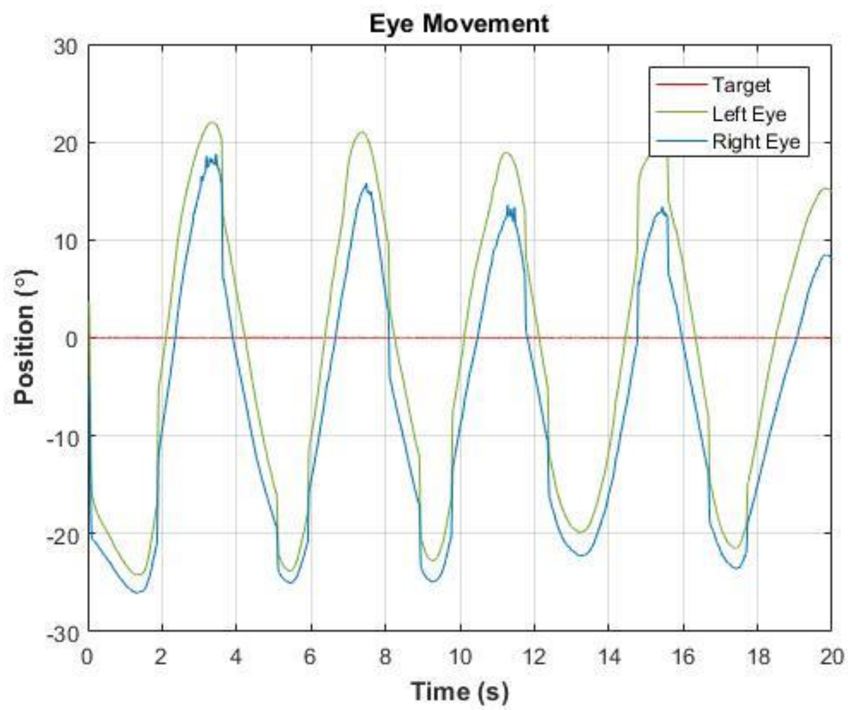

Fig. 4. *Second attempt at imaginary tracking (Trial 10), in which the subject tracked his finger in the dark. Although the tracking being done here is rough in comparison to those resulting from Trials 1-8, it is clear that there is plenty of smooth pursuit present.*

As pursuit in this trial is largely smooth, we can easily measure their respective velocities. For instance, the smooth pursuit velocity at the first zero crossing to the right (just past 2 seconds) is approximately 29.0 °/sec, and other (peak) pursuit velocities could be measured similarly.

Now, which the subject track better: his finger or the imagined target? When comparing the results from Trial 10 (shown in Fig. 4) to those obtained in Trial 9, it is amazing to see just how significant proprioception is for spatial awareness –the subject's ability to *feel* and track the position of the target. Fig. 5 shows the results from Trial 9 and is illustrative in depicting how much more challenging it was for the subject to smoothly pursue an imagined target:

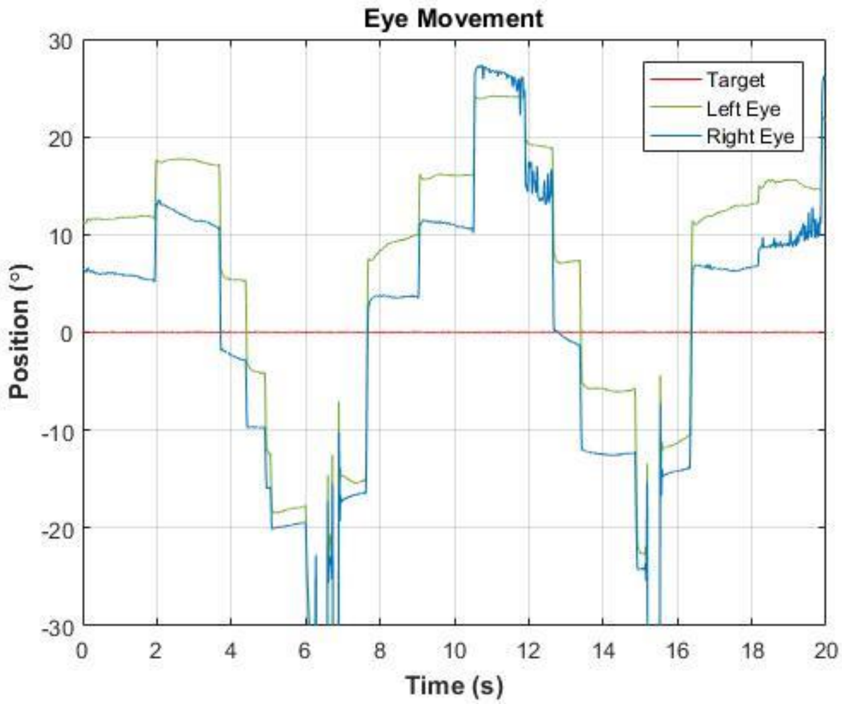

Fig. 5. *First attempt at imaginary tracking (Trial 9), in which the subject tracked an imagined target in the dark. Clearly riddled with saccades, this trial is especially illustrative in showing the importance of proprioception in establishing and maintaining smooth pursuit.*

Question 4.

For the experiment using the feedback of eye position to move the target, the level of *external negative* feedback gain that was necessary to sustain saccadic oscillations was most closely achieved in Trial 18, in which the negative feedback gain was 1.0.

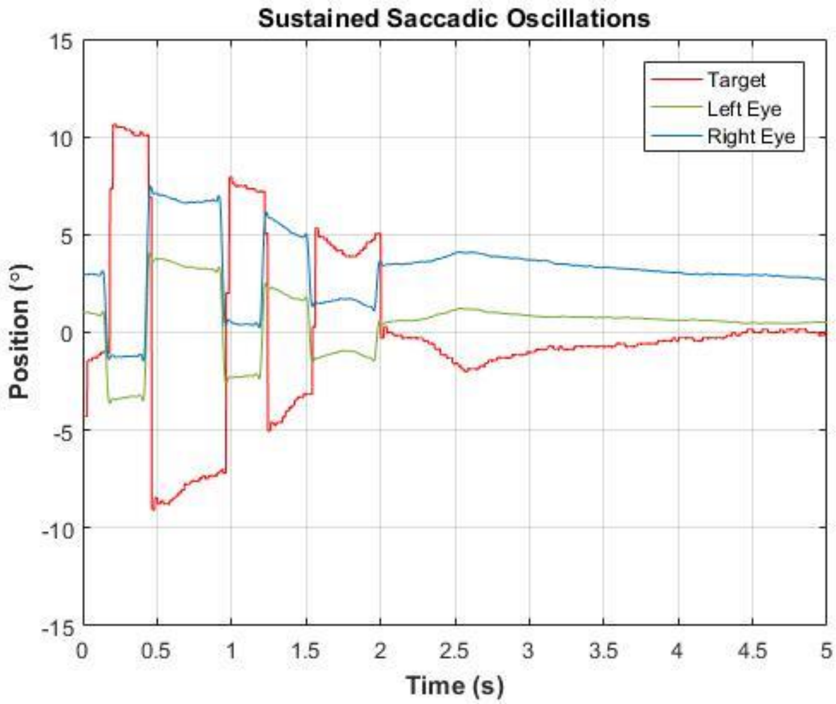

Fig. 6. *Saccadic oscillations achieved in Trial 18 using an external negative feedback gain of 1.0. Although only sustained for a couple seconds, this is trial exhibits the longest-sustained saccadic oscillations across all five trials using negative feedback. For instance, Trial 17 exhibited only half the number of oscillations, and Trial 16 exhibited half of that. On the other hand, Trials 19 and 20 exhibited no sustained saccadic oscillations.*

With regard to what is theoretically expected here, this observation is very close. Since there is intrinsically an internal feedback gain of -1, the external negative feedback gain, A, that would be necessary for achieving a total feedback gain of zero, would theoretically have to be 1, such that

$$FB_T = FB_{int} + FB_{ext} = -1 + A = -1 + (1) = 0$$

Although the results in Fig. 6 do not show perfectly sustained saccadic oscillations, these are perhaps the closest experimental results one could obtain from a single trial with a single subject. Of course, what might account for discrepancies could be the subject's use of corrective anticipation when tracking the target.

Question 5.

For the saccadic tests, let us begin by taking a closer look into the ocular motor system (OMS) response when subjected to two rapid jumps in target position, shown and annotated in Fig. 7.

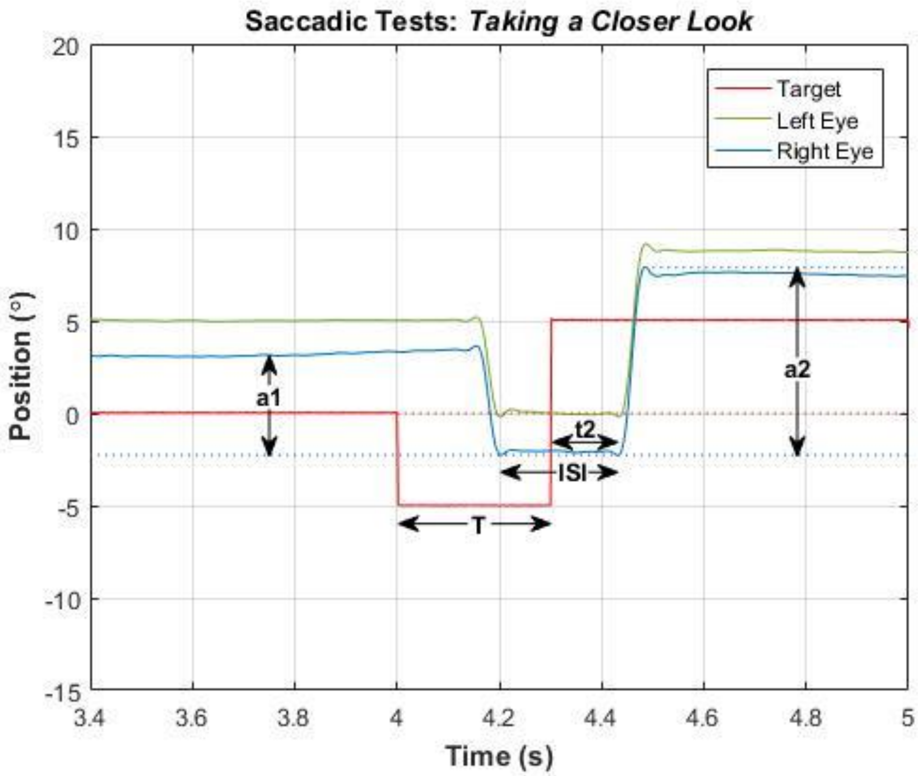

Fig. 7. *OMS response to two back-to-back target jumps in the saccadic tests. The target data is annotated with the delay of the second target jump (T), and annotations for the right eye—ignoring the left—include the following: amplitude of the first saccade (a1), amplitude of the second saccade (a2), latency of the second saccade (t2), and intersaccadic interval (ISI).*

Now, to evaluate these parameters, the saccade pairs can be sorted into each of the eleven different target delays tested in this trial: $T = \{0.02, 0.05, 0.1, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50\}$. With this done, the means for all of the above four parameters ($a1$, $a2$, $t2$, and ISI) were able to be computed. These results are collected in Table 1 in the provided Appendix.

Additionally, these parameters can be graphically shown against the eleven different target delays: the next two figures portray the mean values of $a1$ and $a2$ versus T and then $t2$ and ISI versus T, respectively.

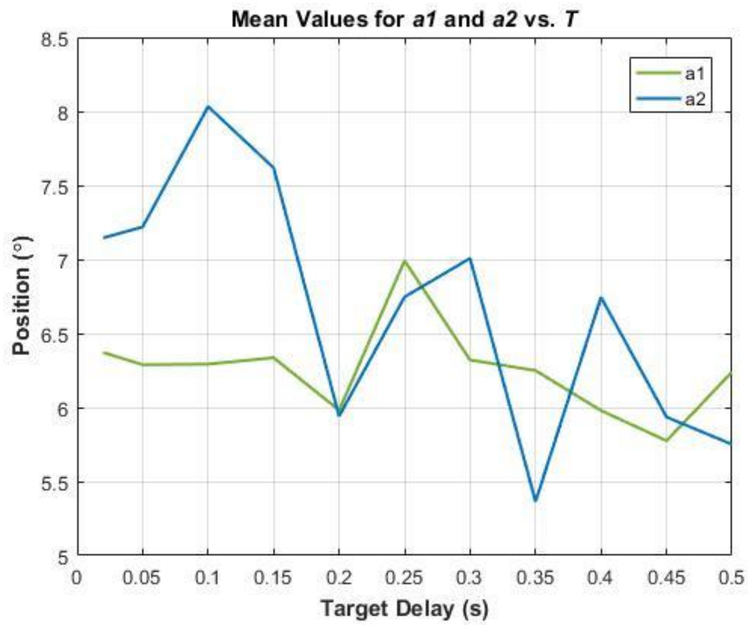

Fig. 8. *Mean values for the first and second saccades (a_1 and a_2) for each of the eleven target delays tested in the six-minute trial, Trial 21. Despite how jagged these results appear, it is clear that there is an overall increase in the mean amplitude of the second saccade as the target delay becomes shorter and shorter. Per contra, as the target delay is elongated, it becomes easier for the subject to follow accurately. This explains the larger discrepancy in amplitude for shorter target delays, versus the relatively more converged amplitudes for longer target delays.*

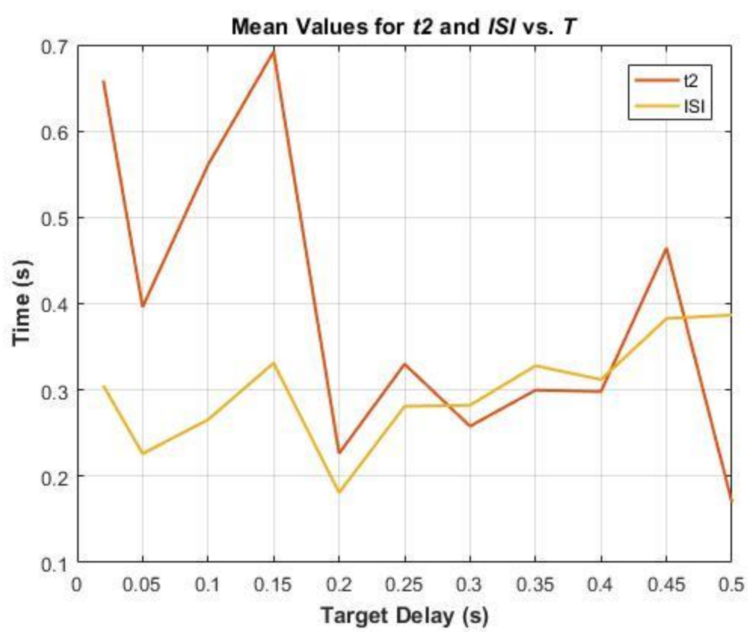

Fig. 9. *Mean values for the latency of the second saccade (t_2) and the intersaccadic interval (ISI) for each of the eleven target delays tested in Trial 21. Once again, like in Fig. 8, the results appear far more converged for longer target delays, as compared to those observed for shorted target delays. This can simply be attributed to the inherent difficulty for the OMS to track very rapid changes in target position. Given the orders of magnitude of acceleration we are capable of using when performing a saccade, tracking a slower-moving target is far easier than it is to track one whose speeds are contingent with our very central nervous system.*

In an ideal world, the values for a_1 and a_2 are expected to be exactly identical, since the target stimulus returns to the same position from which it started before the saccade pair. It is clear from Fig. 8 and Fig. 9 that target delay (T) had a prominent effect on the accuracy of the second saccade. Of course, this does *not* include responses during the six-minute trial consisting of only one saccade, for obvious reasons.

There appears to be a minimum intersaccadic interval of 0.181 seconds, at a target delay of 0.2 seconds. Although it would perhaps make more sense for the intersaccadic interval to have the shortest duration for the shortest target delays, it is important to keep in mind the physical behaviors of the OMS. As discussed in Question 4, saccadic oscillations can be sustained, but only under the right circumstances. Namely, in this case, if the intersaccadic interval is of the appropriate duration, the subject can rebound from the first saccade with greater ease and thus accuracy. As for shorter intersaccadic intervals, the eye cannot recover its initial position in time, losing accuracy. Likewise, for longer intersaccadic intervals, the eye may have to wait with the target before performing the second saccade returning it to its initial position, voiding the eye of its ability to sustain the first saccade in 'bouncing back' to its original position.

Question 6.

In the part of the experiment testing the vestibulo-ocular reflex (VOR) of the subject, the chair was coupled with the laser-galvanometer system. Thus we were able to accurately analyze the effects directly. Figures Fig**. 10**-Fig**. 13** show the results obtained for the VOR tests we performed:

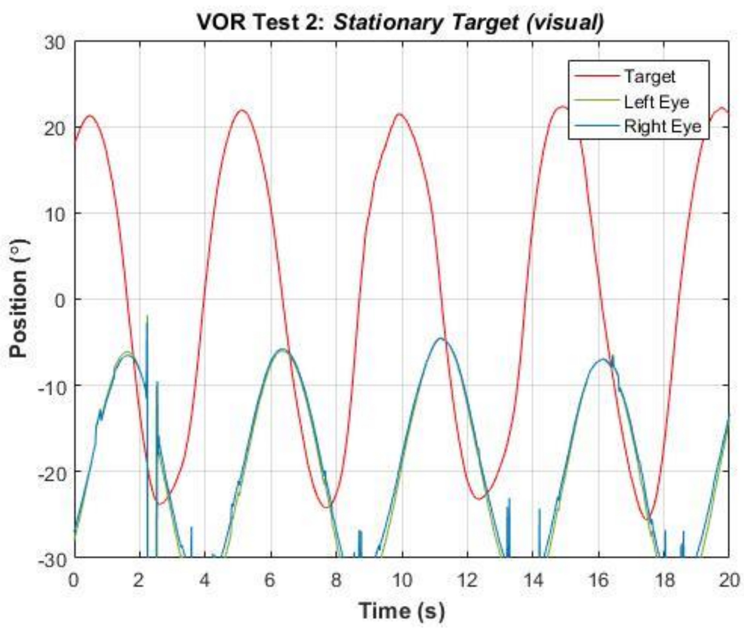

Fig. 10. *Second vestibulo-ocular reflex test, in which the target remained stationary. The gain (average of the peak eye velocity divided by the peak chair velocity) is approximately 0.5002.*

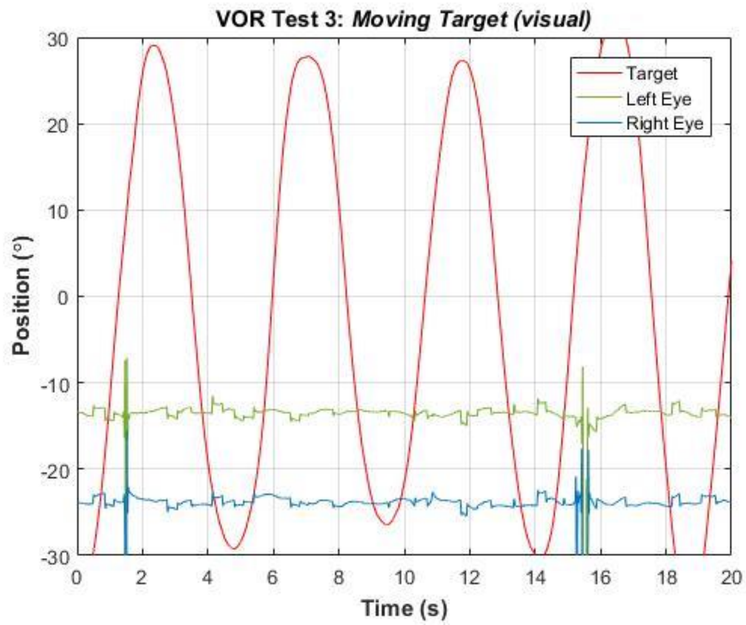

Fig. 11. *Third vestibulo-ocular reflex test, in which the target was moving. This time, the gain was compute to be only about 0.0249 –not a big surprise!*

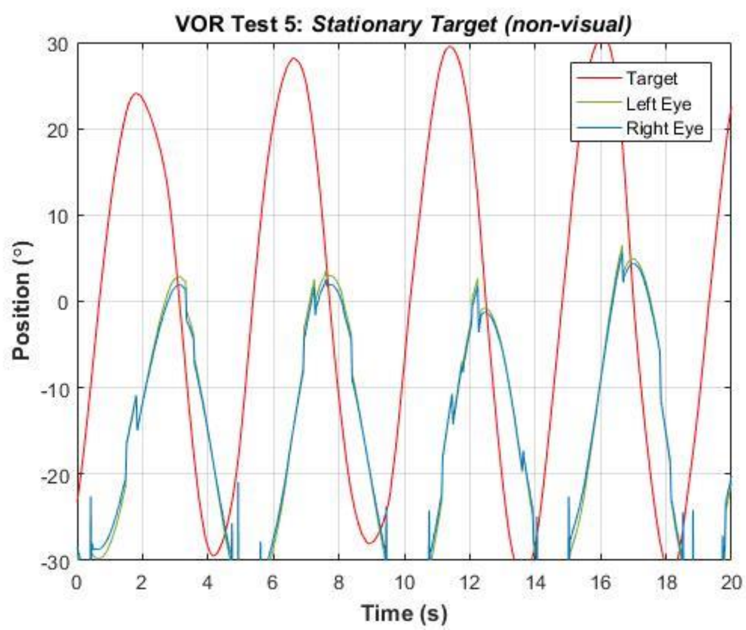

Fig. 12. *Fifth vestibulo-ocular reflex test, in which the target was stationary, but not visible. The gain was found to be approximately 0.6116.*

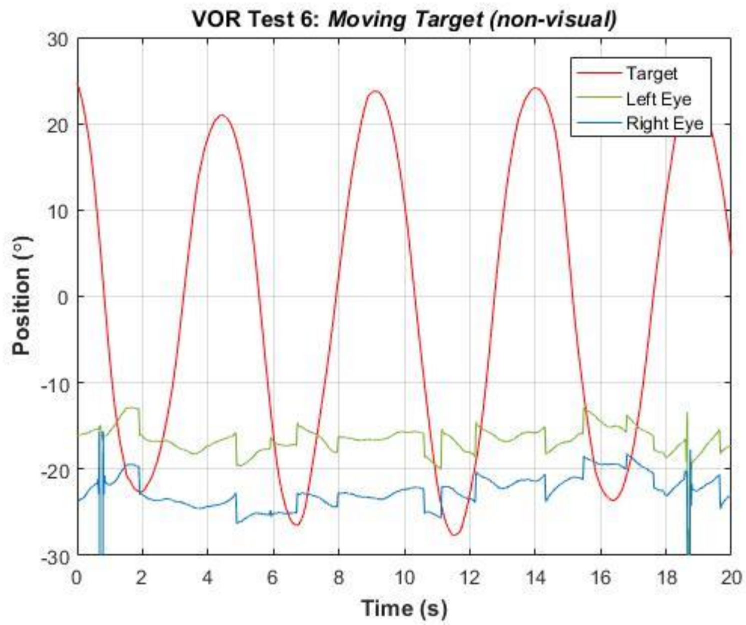

Fig. 13. *Sixth vestibulo-ocular reflex test, in which the target was moving, but not visible. The gain computed for this trial is roughly 0.0624 –an improvement from that in the third test!*

Drawing from evidence and behaviors discussed in prior questions, it makes sense that, the farther the gain is from zero, the more difficult it becomes to accurately track the target. In fact, visual information is critical to our ability to actually *use* our eyes correctly. Simply noting the discrepancy in average gains between Tests 3 vs. 6, in this case, *not having the visual stimulus as a guide*, it becomes roughly three times more difficult to maintain accuracy.

Question 7.

Regrettably, I have run out of time to answer these questions to completion…

V. Conclusion

If I were to add a conclusion, it would appear here...

Please feel free to look at my inspiring MATLAB code in my online repository: https://github.com/teddybear02/omlab

Note that I will soon be moving into my organization here: https://github.com/CWRU-BMELabs-ttf10/omlab

APPENDIX

Table 1. Saccadic latency parameter measurements from Trial 21.

Trial	T	$a1$	$a2$	$t2$	ISI
1	0.50	4.1284	7.3848	0.1660	0.4740
2	0.30	3.6508	7.8977	0.1300	0.2300
3	0.45	3.3562	3.3214	0.6480	0.4820
4	0.20	3.6302	8.2324	0.1620	0.1720
5	0.40	3.7570	7.8689	0.1000	0.3180
6	0.30	3.4876	-1.0595	0.1180	0.1140
7	0.50	3.8296	-0.1600	0.0920	0.3940
8	0.05	4.4311	7.7381	0.2940	0.1540
9	0.50	4.0308	0.5437	0.0980	0.4020
10	0.15	4.7602	4.7602	1.8440	0.0000
12	0.40	4.7033	9.3171	0.1220	0.1920
13	0.02	4.4834	8.6489	0.4100	0.2440
14	0.05	4.0842	-0.6928	0.6480	0.5260
15	0.10	5.0207	7.9130	0.2800	0.1940
17	0.20	4.9608	-0.1534	0.1460	0.1600
18	0.20	5.3118	11.1021	0.1200	0.1380
19	0.45	4.7731	4.1312	0.6460	0.4620
20	0.05	5.0620	5.0620	1.9460	0.0000
21	0.45	5.3281	6.1008	0.6540	0.4760
22	0.35	5.3585	6.3595	0.6480	0.4960
23	0.40	5.2626	5.2246	0.5100	0.3580
24	0.35	5.6745	10.1623	0.1160	0.2500
25	0.10	5.1304	5.0520	0.9020	0.3880
26	0.05	5.1267	5.1267	-1.0480	0.0000
27	0.10	5.3560	5.3560	0.8960	0.0000
28	0.02	5.4723	5.4723	-0.0260	0.0000
29	0.15	5.3852	6.1412	0.6480	0.2760
30	0.45	5.4412	5.7320	0.4920	0.3420
31	0.20	5.2309	-0.1563	0.1360	0.1280
32	0.40	5.7576	5.5816	0.4700	0.2940
33	0.40	5.3511	5.3046	0.4400	0.2820
34	0.15	5.9146	8.9156	0.5200	0.4580
35	0.15	5.5825	5.9588	0.8020	0.3260
36	0.35	5.8122	4.5369	0.4480	0.2700
37	0.45	5.6142	6.0256	0.4580	0.2960
38	0.15	6.1859	5.7920	0.5580	0.4060
39	0.25	5.2456	4.7664	0.5200	0.3540
40	0.35	5.9822	6.3061	0.5240	0.3860
41	0.40	5.7146	4.1318	0.0540	0.2620
42	0.25	6.4150	1.6475	0.1080	0.1800
43	0.05	6.2778	6.6342	0.7660	0.3900
44	0.10	6.1439	9.9306	0.2900	0.2220
45	0.45	6.4471	4.4082	0.0580	0.3000
46	0.02	6.9082	6.9082	-0.0160	0.0000
47	0.45	6.6743	6.3041	0.4920	0.3380
48	0.10	6.4434	7.7750	0.7060	0.3780
49	0.10	6.4995	9.5035	0.3100	0.2200
51	0.25	6.6800	10.4519	0.3360	0.2060
52	0.25	6.7067	5.8204	0.7380	0.5620
53	0.20	6.7985	10.8558	0.1420	0.0460
54	0.25	6.1964	6.6915	0.5540	0.3800
55	0.25	6.1107	6.8431	0.5240	0.3440
56	0.05	6.4370	6.7996	1.0340	0.5300

57	0.40	6.7043	3.5890	0.0980	0.3140
58	0.20	6.8555	3.7908	0.1320	0.1200
59	0.40	7.1689	7.0575	0.6240	0.4660
60	0.30	7.0916	6.7883	0.4960	0.3440
61	0.15	6.6654	7.2346	0.6200	0.4200
62	0.45	6.9272	7.5541	0.5180	0.3520
63	0.50	6.9335	5.8664	0.4880	0.3340
64	0.20	6.2083	6.3679	0.5440	0.3580
65	0.05	6.5713	6.5713	-1.0500	0.0000
66	0.10	6.7089	7.1352	1.0580	0.5980
67	0.35	6.9806	7.1235	0.7020	0.5320
68	0.35	7.3449	11.2606	0.0920	0.2600
69	0.20	7.4464	7.5154	0.5420	0.3780
70	0.02	6.9903	8.6142	0.8680	0.4900
71	0.30	6.8725	7.2873	0.5420	0.5040
72	0.15	7.2658	7.2169	0.7440	0.4600
73	0.20	6.8205	10.4356	0.1800	0.1780
77	0.30	7.2151	11.4665	0.1660	0.2620
79	0.30	6.2787	10.5423	0.1320	0.2280
80	0.35	5.8576	1.2532	0.1240	0.2880
81	0.02	5.8053	5.8327	0.7820	0.4460
82	0.02	6.5010	7.5674	0.8780	0.4300
83	0.35	6.3553	2.0182	0.1220	0.2880
84	0.20	6.5466	1.4202	0.1600	0.1320
85	0.02	5.6293	6.5740	0.7980	0.3360
86	0.35	6.2236	2.2228	0.1020	0.2780
87	0.10	6.5723	10.3742	0.1840	0.1120
88	0.45	6.8662	6.5473	0.5900	0.4280
89	0.05	7.8250	6.7965	0.7440	0.2940
91	0.30	6.4949	12.4110	0.1240	0.2140
92	0.45	6.3197	9.2271	0.0880	0.3520
93	0.50	6.6425	6.7525	0.0120	0.3180
94	0.02	6.6736	7.2756	0.8940	0.4500
95	0.50	6.8573	3.8001	0.0620	0.3720
96	0.02	7.6401	6.4114	1.0860	0.2940
97	0.35	6.9044	2.3976	0.1200	0.2320
98	0.15	7.2190	11.9720	0.1620	0.1360
99	0.50	7.1223	6.2266	0.0380	0.3600
100	0.15	7.1676	12.4480	0.4420	0.4280
101	0.30	7.3111	3.4509	0.1240	0.2280
102	0.15	7.2142	5.7473	0.5800	0.4020
103	0.30	7.1244	3.0571	0.1040	0.2240
104	0.25	8.2212	2.6216	0.1520	0.2140
105	0.50	7.3151	7.5222	0.0000	0.3180
106	0.30	7.6809	8.2323	0.6440	0.4760
107	0.40	7.6026	11.2506	0.0960	0.3260
108	0.02	7.6070	8.1503	0.9140	0.3600
109	0.25	7.7172	2.6636	0.1260	0.1860
110	0.50	7.1608	8.2142	0.6500	0.4900
111	0.10	8.0349	7.5590	0.5380	0.3600
113	0.40	7.7668	8.1116	0.4680	0.3080
114	0.50	8.3789	11.3528	0.0920	0.4060
115	0.25	8.0039	12.3895	0.1260	0.1880
116	0.10	7.0140	9.7227	0.4460	0.1840
117	0.25	8.6129	13.5708	0.1160	0.1960
118	0.05	8.4413	14.5489	0.2860	0.1460
119	0.05	8.6285	13.6071	0.3420	0.2220
	0.02	6.3710	7.1455	0.6588	0.3050
/	0.05	6.2885	7.2192	0.3962	0.2262
|	0.10	6.2924	8.0321	0.5610	0.2656

|	0.15	6.3360	7.6186	0.6920	0.3312
|	0.20	5.9810	5.9410	0.2264	0.1810
Means	0.25	6.9910	6.7466	0.3300	0.2810
|	0.30	6.3208	7.0074	0.2580	0.2824
|	0.35	6.2494	5.3641	0.2998	0.3280
|	0.40	5.9789	6.7437	0.2982	0.3120
\	0.45	5.7747	5.9352	0.4644	0.3828
	0.50	6.2399	5.7503	0.1698	0.3868

Acknowledgement

I would like to take a moment to thank Dr. Jacobs for the opportunity to participate in such a fascinating experiment! Being allowed to use the array of state-of-the-art equipment in the Daroff-Dell'Osso Ocular Motility Laboratory (OMLAB) was especially fun and memorable.

References

[1] L. A. Abel, D. Schmidt, L. F. Dell'Osso and R. B. Daroff, "Saccadic system plasticity in humans," *Annals of NeuroIogy*, vol. 4, no. 4, pp. 313-318, October 1978.

[2] J. A. Sharpe and T. O. Sylvester, "Effect of aging on horizontal smooth pursuit," *Investigative Ophthalmology and Visual Science*, vol. 17, no. 5, pp. 465-480, May 1978.