VIRTUAL REALITY GAZE DIRECTION VIA A DYNAMIC REAL-TIME COLOR EFFECT

A Thesis

by

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ABSTRACT

For developers of immersive 360-degree virtual environments (VEs), directing the viewer's gaze towards points of interest (POIs) is a challenge. Limited research exists testing the effectiveness of various gaze direction techniques. However, there is a lack of empirical research evaluating dynamic, full-image color effects designed to direct the viewer's gaze. I have developed a novel VR gaze-directing stimulus using a dynamic real-time color effect and tested its effectiveness in a user study. The stimulus was influenced by color psychology research and chosen by participants in an informal pilot study. Results suggest that, in certain cases, the stimulus successfully re-directed viewer gaze towards POIs. While the task of *holding* viewer gaze in VR remains a challenge, the stimulus tested in this experiment has potential as a simple and customizable addition to the existing toolset of VR gaze-directing stimuli.

DEDICATION

To science: the pursuit of truth, and to God: the source of all truth.

ACKNOWLEDGEMENTS

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Many thanks to my friends and colleagues, and to the Department of Visualization faculty and staff for helping make this research possible.

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Contributors

This work was supervised by a thesis committee consisting of Professor Ann McNamara and Professor Eric Ragan of the Department of Visualization, and Professor Ricardo Gutierrez-Osuna of Computer Science and Engineering.

All work for the thesis was completed independently by the student.

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NOMENCLATURE

VR	Virtual reality
VE	Virtual environment
POI	Point of interest
HMD	Head-mounted display
3D	3-dimensional
FOV	Field of view
SSQ	Simulator Sickness Questionnaire
ANOVA	Analysis of variance

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1. INTRODUCTION

1.1 Introduction

When viewing virtual environments (VEs), the viewer's field of view (FOV) is smaller than the entire VE that can be perceived. In 360-degree VEs with distinct POIs, there is a risk that the viewer will miss certain POIs because they have the freedom to look about the VE as they choose. Figure 1.1 shows how a viewer might miss points of interest in Baobab Studios' "Invasion" VR experience [23]. When wearing a head-mounted display (HMD), the viewer is the "director" of the experience with free control of the camera. This presents a problem for VR developers.

Figure 1.1: Screencaps adapted from Baobab Studios' "Invasion" VR experience demonstrating that the viewer has the freedom to pay attention to POIs (left) or not (right).

Limited research exists which explores solutions to the challenge directing viewer gaze to POIs in VR. These techniques include distraction by digital characters [13, 14, 15] and graphical cues super-imposed over POIs [1, 9].

Using extra objects or characters to guide attention can prove extraneous and impose design constraints on VR developers. Whereas these techniques rely on additive visual elements, my method simply modifies an already-existing element: the rendered image itself. While there exists research evaluating VR post-processing effects as gaze direction devices [4], none of these effects consider color as a parameter for testing. I aimed to guide VR gaze by modifying the rendered color of the VE with a dynamic image processing effect.

Gestalt theories of perception [10] state that color can affect the saliency of an image. In the field of color psychology research, several studies have recorded that the hue yellow ranks among the lowest in pleasantness ratings [5], is among the least popular hues [16], is one of the least preferred hues [7] and holds the high anxiety scores and low pleasure levels [18]. Through an informal pilot study, yellow was voted the most uncomfortable hue when compared to six other hues.

2. LITERATURE REVIEW

2.1 Gaze Direction in 3D Environments

Research on gaze direction in a 3D environment has been documented as early as 1996, with Disney Imagineering's "Aladdin" VR attraction [13]. Within the virtual environment, characters gestured or moved towards POIs with the hope that the viewer's gaze would follow their signaling.

Studies by Peck, et al. reported on the reorienting effects of 3D "distractors" such as spheres, butterflies, and birds [14, 15]. When participants moved close to the bounds of the real space, these elements appeared in the viewer's FOV and drew their gaze horizontally while the entire VE rotated accordingly. This technique discretely re-oriented the viewer, allowing them to navigate VEs that were larger than the area of the real-world physical space allotted for viewing the VE.

A depth-of-field blur effect was used by Hillaire et al. to direct the gaze of players of a 3D first-person shooter game toward the center reticle of the user interface [6]. They found that the effect aided less-experienced players in game performance factors such as shooting precision.

3D focal planes have been used to emphasize certain parts of a 3D image [2]. An experiment by F. Cole et al. used local variations in rendered line width, color, and sharpness to distinguish POIs. A dynamic 3D plane defined these localized stylistic variations. In a user study informed by eye tracking, their method was shown to effectively direct viewer gaze.

"Subtle gaze direction" (SGD) [1] is a technique whereby attention-capturing modulations in color warmth and luminance appear and disappear rapidly over POIs. Research on SGD evaluated small localized image modulations which appeared and disappeared rapidly over POIs in the viewer's peripheral vision. The modulations directed viewer gaze before the viewer could notice them [12]. Further experiments using SGD showed improved search task performance without affecting the user's perception of the search task environment [9]. This technique has obvious implications for VR.

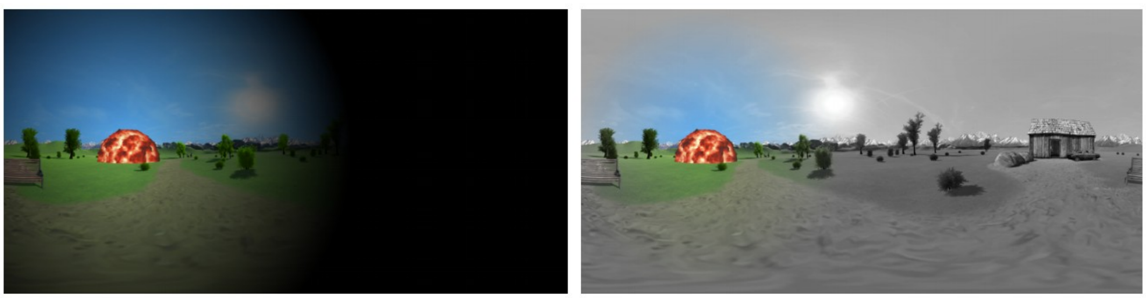

Figure 2.1: 360-degree images of VEs from an experiment by Danieau et al. showing their full-image fade-to-black and color desaturation gaze direction stimuli. Reprinted with permission.

A 2017 study by Danieau et al. tested the gaze-directing effects of full-image post-processing in VR [4]. When participants looked away from POIs, the rendered image as viewed through the HMD would change according to a pre-defined image effect. The rendered image would return to normal as viewers returned their gaze back toward POIs. The effects that were evaluated were fade-to-black and color de-saturation (see Figure 2.1). While results suggested that these dynamic effects could discourage viewer gaze from straying, study participants reported the effects to be disturbing and uncomfortable to view.

2.2 Color Psychology

Experiments in color psychology use color as independent variables and behavioral responses as dependent variables [20]. The effects of color on a person's behavior are complex. A single color may affect people differently depending on their age, mood, cultural background, learned responses, or other factors [3]. Furthermore, claims to these effects are often influenced by speculation and pop culture [11]. Since 1950 and with the development of the Semantic Differential, systems of color preferences have been more established by scientific inquiry rather than by speculative claims.

Several color psychology studies have recorded that yellow has repulsive effects on subjects. Yellow and yellow-green have ranked lowest in pleasantness ratings [5]. A study conducted by Rider [16] found that yellow was the least popular hue. Jacobs and Suess [7] conducted studies which yielded the following ranking of hues from most preferred to least preferred: blue, green, purple, violet, orange, and yellow. In a study on anxiety and pleasure responses to various hues, red and yellow held the highest anxiety scores and yellow, green-yellow, and yellow-red had the lowest pleasure levels [18].

3. METHODOLOGY

3.1 Goals and Hypotheses

My goal was to develop a VR gaze direction stimulus that was not an extra object or character. The stimulus would affect the full rendered view of the HMD, similar to the stimuli tested by Danieau et al [4]. However, like in SGD [1], the stimulus would be a color-based image processing function. The strength of such a stimulus would need to be informed by viewer gaze in real time, not adversely affect the VE's frame rate, and not cause the viewer significant discomfort.

I conducted an experiment investigating how a dynamic real-time color effect influenced viewer gaze in a VE. With the color effect as my independent variable, I would test its effects on the following dependent variables: head orientation angle, eye gaze, VE comprehension, and reported simulator-related symptoms. I formed the following hypotheses:

- **H1**: The stimulus would successfully re-direct viewer gaze.
- **H2**: Gaze data would show more favorable performance with the color effect.
- **H3**: The color effect would not significantly increase simulator-related sickness among participants.
- **H4**: The color effect would improve VE comprehension scores.

3.2 Pilot Study

The role of the stimulus in this experiment was to increase the rendered image's level of visual discomfort when the viewer looked away from the POI. While the color red may seem like the obvious hue to use, the aforementioned color psychology research suggested that yellow might be a more appropriate choice [5, 7, 16, 18]. To verify the choice of yellow as an "uncomfortable" hue, a pilot study was conducted.

Six sighted adults volunteered as participants in an informal voluntary pilot study to determine the hue and intensity of the color effect we were to evaluate. The experiment was presented in a computer program and distributed electronically to each participant (see Appendix).

Figure 3.1: Hue options from the informal pilot study: normal, yellow, blue, cyan, green, red, violet, and orange.

The pilot study was given in two parts. In Part 1, participants viewed 8 static images, two at a time, and chose the most uncomfortable image in a single elimination bracket format (see Figure 3.1). It was hypothesized that yellow would be the hue chosen most often by the participants.

In Part 2, participants indicated their perceived threshold of discomfort of the image they chose in a modified staircase procedure where t_a is the threshold with ascending stimulus strength and t_d is the threshold with descending stimulus strength. In the first part of the procedure, the image's color started normal and gradually turned more yellow by 10% every 3 seconds. Participants were instructed to click on the image as soon as it became "uncomfortable" to view. Next, the image started at 100% strength and decreased in strength by 10% every 3 seconds until its color returned to normal. Participants were instructed to indicate when the image was "comfortable" to view once more by clicking it.

Table 1 shows the results for each participant. The results supported the hypothesis: the mode of the hues chosen to be the most uncomfortable to look at among the eight hue choices was yellow. The rounded mean perceptual threshold of discomfort among the six participants was 63% color filter strength (s = 14.9). Thus, the minimum strength of the color effect that would be evaluated was 63%.

Participant	**Hue**	t_a	t_d
1	violet	70%	40%
2	orange	40%	50%
3	yellow	80%	60%
4	violet	80%	50%
5	yellow	70%	60%
6	yellow	80%	80%

Table 1: Most uncomfortable hues and perceived thresholds of discomfort in ascending and descending strength.

Using such a color effect at 100% strength may impose design constraints on VR developers who have a specific color scheme in mind for the VE. In the interest of preserving the original rendered color of the VE as much as possible, it was determined to evaluate the yellow color effect at both full strength and at the minimum perceived level of discomfort. Therefore, participants would be assigned to one of three groups:

- **Group 1:** Control Group (0% maximum stimulus strength)
- **Group 2:** Full Stimulus Group (100% maximum strength)
- **Group 3:** Reduced Stimulus Group (63% maximum strength).

3.3 Virtual Environments

Three VEs were created for the experiment (see Figure 3.2). The goal was to create environments that would not adversely affect the frame rate of the virtual experience. A simplified 3D modern city with visual elements all around the viewer's position was used for each VE. It was determined that a familiar real-world environment would help avoid bias in the participants' gaze data due to being confronted with totally unfamiliar surroundings. Because this experiment evaluated a visual stimulus, the VEs had no sound. Each scene's POI changed at set intervals and the action could be easily missed by the viewer. The VEs and their respective POIs were designed as follows:

- **VE1**: Viewer is on a balcony overlooking a street. POI is a billboard showing an image of a coffee mug. After 20 seconds, the image changes to a car. 10 seconds after that, the image changes to some kittens.
- **VE2**: Viewer is seated at a table on a sidewalk. POI is a telephone booth. After 25 seconds, a man in a yellow shirt enters the booth.
- **VE3**: Viewer is seated in a car. POI was two cars at a traffic stop. After 32 seconds have passed, the cyan car drives forward with the orange SUV following it.

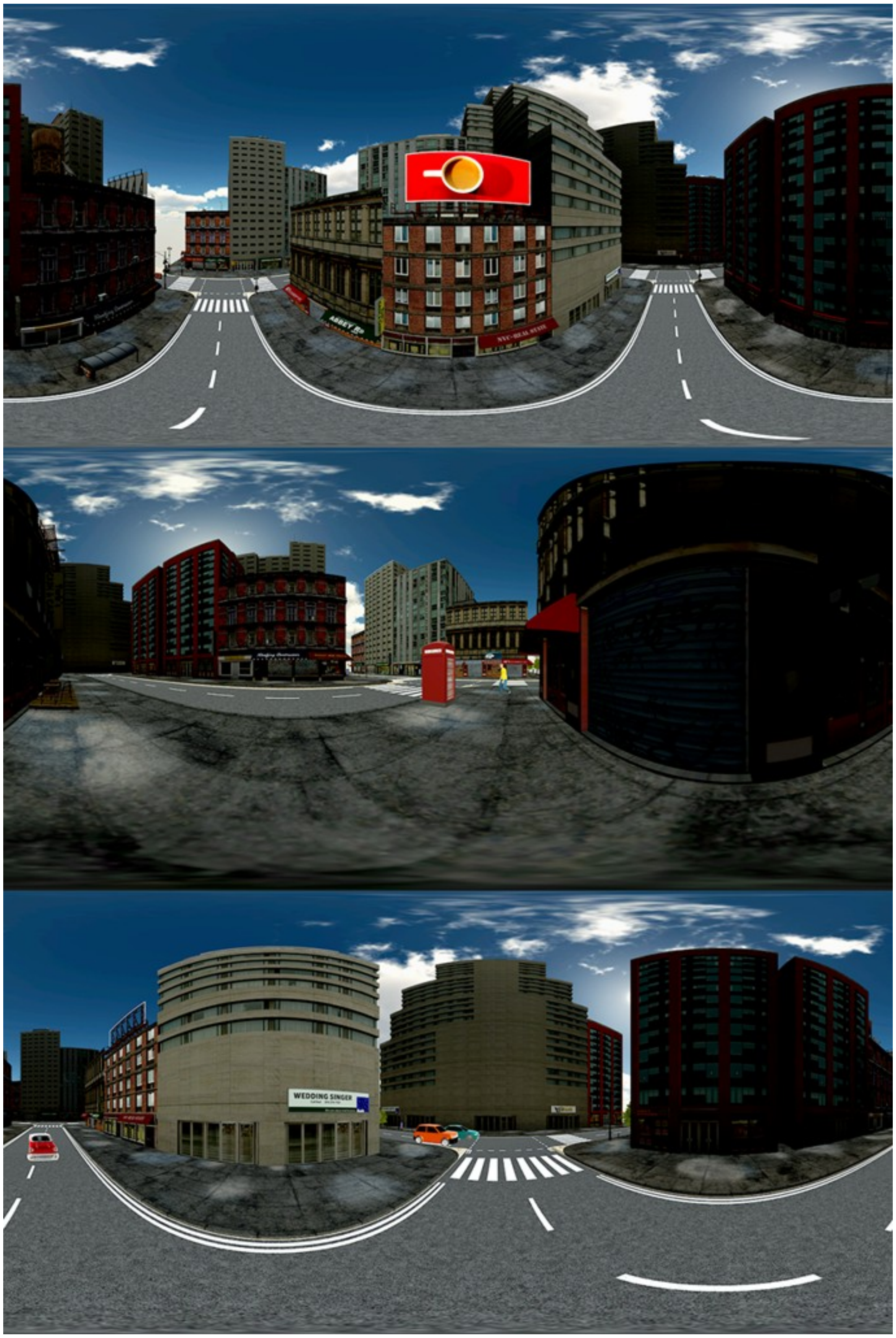

Figure 3.2: 360-degree images of the VEs created for the experiment.

3.4 Stimulus

The yellow color effect was created by adjusting the blue channel curve of the rendered image in a Unity script using the free Dynamic Color Correction plugin available in the Unity Asset Store [22]. By lowering the output value of the blue channel curve, the rendered image acquired a yellow hue (see Figure 3.3).

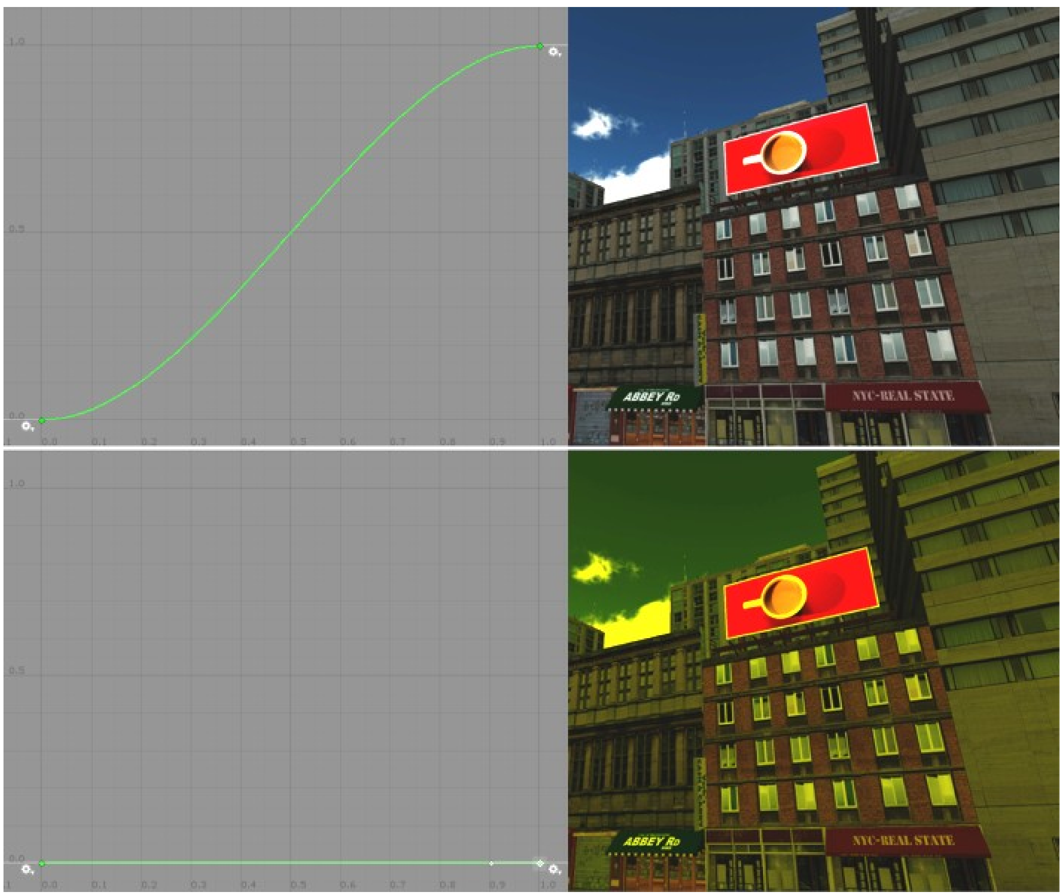

Figure 3.3: Effect of decreasing the rendered image's blue channel curve output (left) on the rendered image (right).

The new output color (R_o,G_o,B_o) of the rendered image would reflect the adjustment input to the blue channel B_i:

$$(R_o,G_o,B_o) = (R_i,G_i,B_i) \quad (1)$$

The minimum value of B_i, the modified blue channel, for each participant group was defined as follows:

- **Control Group:** B_i = (1 - 0) = 1
- **Full Stimulus Group:** B_i = (1 - 1) = 0
- **Reduced Stimulus Group:** B_i = (1 - 0.63) = 0.37

The angle difference between the HMD's forward vector within the VE and a vector pointing from the render camera to the POI was calculated for every game engine update cycle. In the Dynamic Color Correction plugin, a "blend" variable linearly blended the rendered image between normal color and the new output color. For every update cycle, the "blend" variable b was calculated as a normalized ratio of the maximum viewer gaze angle from the POI:

$$b = ((\theta - 8) / 180)\ s \quad (2)$$

where θ is the angle difference between the viewer's head orientation and the POI. The angle difference θ is modified by a visual "dead zone" that accounts for the physical space that each POI occupies. Tests using eye tracking helped determine 8 degrees to be a suitable value for the angle of error. The variable s is a sensitivity multiplier that uniformly amplifies the perceived change in rendered color. After trial and error, the value s = 2 was deemed an appropriate value for stimulus sensitivity. Thus the angle difference θ was the basis for informing the strength of the stimulus in real time.

Figure 3.4 shows the stimulus dynamically blending the rendered image of the VE between the default blue channel curve and the adjusted blue channel curve. As the participant looked away from the POI, the intensity of the rendered color effect increased in real time. As the participant's gaze returned to the POI, the rendered colors gradually returned to normal.

Figure 3.4: The full-image effect dynamically changes the rendered image in real time as the viewer looks away from the POI. The pink circles represent viewer binocular gaze.

3.5 Apparatus

Figure 3.5 shows the physical setup for the experiment. Study participants viewed the VEs with the HTC VIVE HMD [26]. The VIVE has a refresh rate of 90 Hz with a display resolution of 1080 x 1200 pixels for each eye. Embedded in the HMD were eye tracking cameras and sensors by Pupil Labs with a refresh rate of 120 Hz [25]. The HMD was connected to a computer with the following specifications:

- **Operating System**: Windows 10 64-bit
- **Processors**: Intel Core i7-5820K CPU @ 3.30 GHz
- **RAM**: 16 GB
- **Graphics Card**: NVIDIA GeForce GTX 980

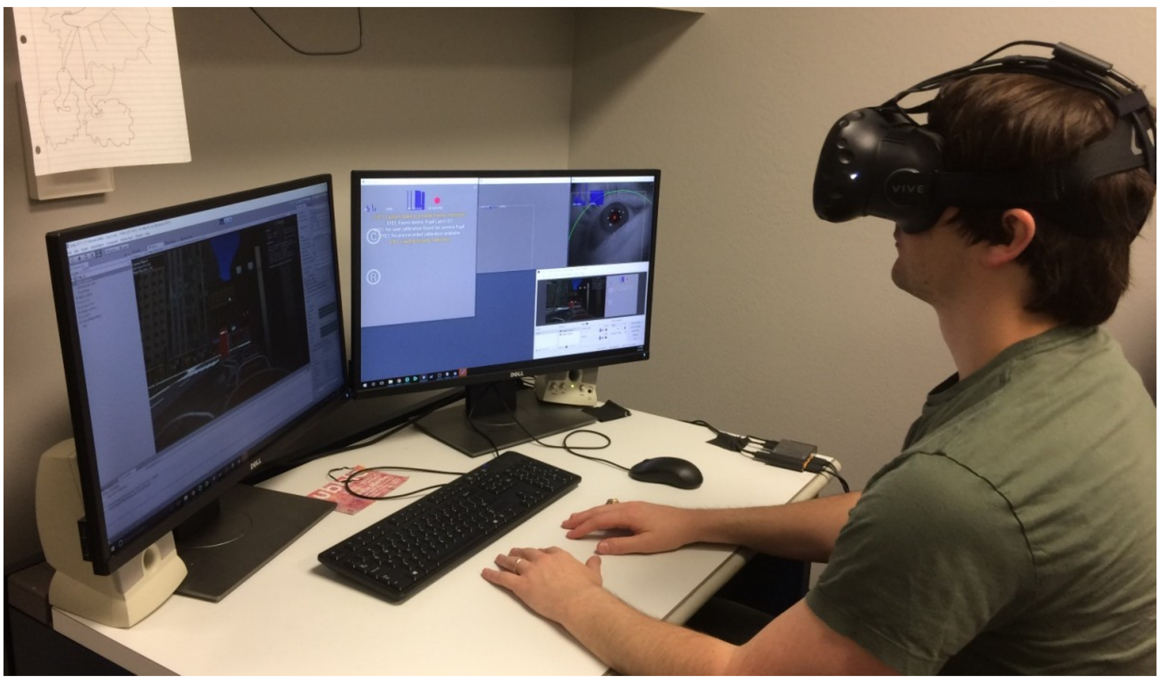

Figure 3.5: The experimenter seated at the physical computer setup used for the experiment.

Participants were seated in a rolling chair that could rotate in place. By turning in the chair, participants could look all around them if they chose. For the purpose of comfort, participants were seated at a table and were allowed to rest their arms on it if they chose to. VIVE handheld controls were not used.

3.6 Participants

Thirty participants volunteered to take part in the study. Participants were sighted adults with normal or correct-to-normal vision who were able to sit down and wear an HMD for up to 5 minutes. No participants wore glasses as their eyewear would interfere with the eye tracking sensors.

In a pre-study questionnaire (see Appendix), participants self-reported their level of experience with electronic games and VR (not experienced, somewhat experienced, very experienced). Assigning numerical values to the three possible levels of experience (0, 1, and 2 respectively), we find the average participant was at least somewhat experienced in games ($\bar{x} = 1.73$) and less than somewhat experienced in VR ($\bar{x} = 0.73$).

3.7 Procedure

Participants were assigned to one of the three experiment groups. The experimenter assisted with putting on the HMD, calibrating the eye trackers, and loading each VE. After a brief orientation/eye tracker calibration stage, participants viewed VE1, VE2, and VE3 in succession. This set order was chosen to see if the yellow color effect could be learned by participants. They were told to view each virtual scene and that they would be asked questions about the VEs afterward. Each participant was allowed to look around in the VE freely. Each VE ran for 40 seconds. 40 seconds was chosen as a duration adequate for showing the actions of the POIs and minimizing viewer discomfort.

After 10 seconds (time needed for the eye trackers to initialize), the gaze-directing stimulus was activated for the Full and Reduced Stimulus groups. The software began recording their gaze tracking data at a rate of 6 samples per second. This sample rate was chosen so that application frame rate did not suffer. The participant's head orientation relative to the POI was recorded. By way of the Pupil Labs Pupil Capture plug-in [24], the screen-space coordinates of the participants' tracked eye gaze was recorded at each sample point. A 3D ray traversing through them was also calculated. If the ray entered within the POI's "dead zone", a value of 1 was recorded for that sample point. If it did not, a value of zero was recorded.

After viewing all three VEs, the experimenter assisted in removing the HMD. Participants completed a Simulator Sickness Questionnaire (SSQ) [8] and a three-item questionnaire to assess their comprehension of the VEs. The following comprehension questions were asked:

- **VE1:** What were the images shown on the billboard? (*Answer: a coffee mug, a car, and kittens*)
- **VE2:** What was the color of the shirt of the man who entered the telephone booth? (*Answer: yellow*)
- **VE3:** Which car drove away from the traffic stop first? (*Answer: the cyan car*).

A completely correct answer was recorded as a score of 1, a partially correct answer (for example, only writing down one or two of the billboard images) held a value of 0.5, and an incorrect or non-answer was valued at zero. Written answers were visually analyzed to detect different variations of the same correct answer (i.e. simply writing "mug" instead of "coffee mug", or answering that the car was blue or teal rather than cyan).

4. RESULTS

4.1 Head Orientation Relative to POI Over Time

The angle difference between each participant's head orientation vector and the vector from the main camera to the POI per sample point was presented graphically (see Appendix). Three of these graphs, one for each VE, were compiled for each of the thirty participants. This data would form the basis of my analysis to find whether or not the stimulus successfully re-directed viewer gaze.

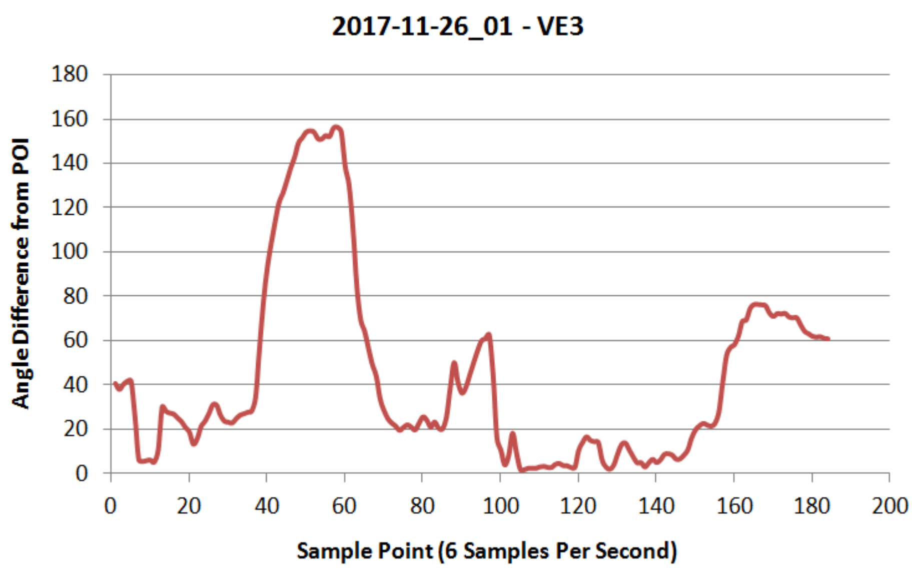

Figure 4.1: Example of a participant's gaze data line graph. Higher values correspond to the participant looking further away from the POI.

Upon visual inspection of these graphs, distinct rising and falling patterns can be observed, which represent the viewer looking away from the POI and then returning their gaze to it (see Figure 4.1). By setting constraints representing minimum and maximum angle difference and a specific number of sample points, I could analyze the data for patterns suggesting that the participant looked away from the POI enough to notice the yellow color effect and then returned their gaze back toward the POI.

A maximum angle difference of 60 degrees was used for the upper constraint. This means the POI would have to be at least 5 degrees out of range of the FOV for the VIVE [26]. A lower constraint of 8 degrees was used to account for the "dead zone" around each POI as per the experiment's design. A value of 18 sample points, or 3 seconds, was determined to be an appropriate length of time for a participant to notice the yellow color effect and return their gaze to the POI. Thus the head orientation graphs for all three participant groups were analyzed for patterns showing the participant's head angle straying at least 60 degrees from the POI and then returning to within 8 degrees of the POI within 3 seconds. Figures 4.2 and 4.3 show this pattern within example gaze data graphs for the Full and Reduced Stimulus groups.

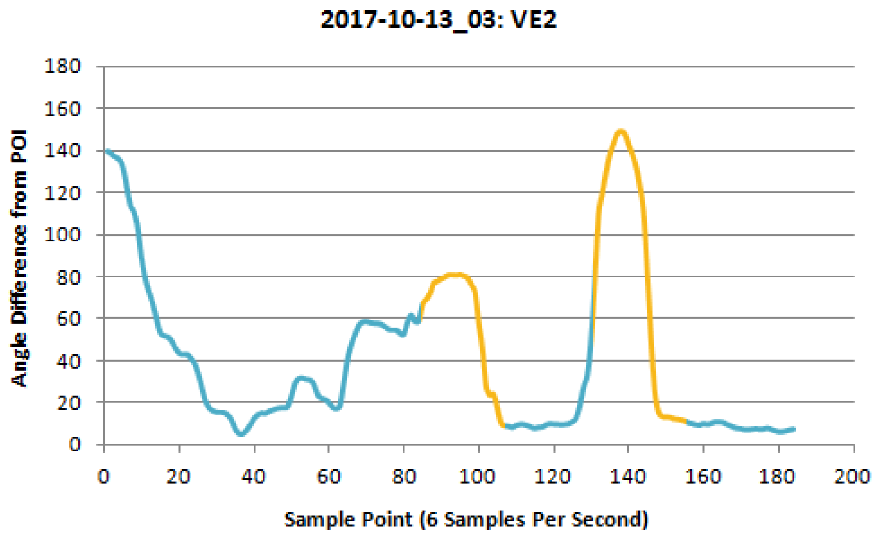

Figure 4.2: Gaze data patterns from a participant in the Full Stimulus Group. Patterns where the viewer's gaze strayed further than 60 degrees from the POI and then returned back to inside 8 degrees within 3 seconds are highlighted in orange.

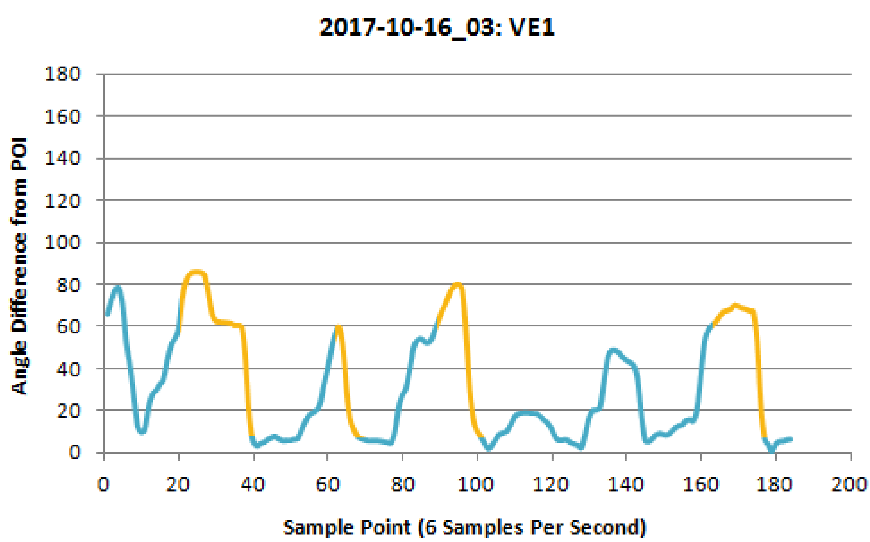

Figure 4.3: Gaze data patterns from a participant in the Reduced Stimulus Group. Patterns where the viewer's gaze strayed further than 60 degrees from the POI and then returned to inside 8 degrees within 3 seconds are highlighted in orange.

After analyzing the head orientation angle data for the three VEs for each participant in each experiment group, the mean rate of occurrence of the previously defined rising and falling pattern per participant for each group was calculated (see Figure 4.4). One-way independent ANOVA test yielded a significant difference between group means [$F(2,87) = 7.19$, $p = 0.001$]. Post hoc Tukey HSD tests showed that the Reduced Stimulus Group ($\bar{x} = 1.47$, $s = 1.20$) and the Control Group ($\bar{x} = 0.50$, $s = 0.68$) differed significantly at $p < 0.01$. The Full Stimulus Group ($\bar{x} = 0.9$, $s = 1.03$) was not significantly different from the other two groups.

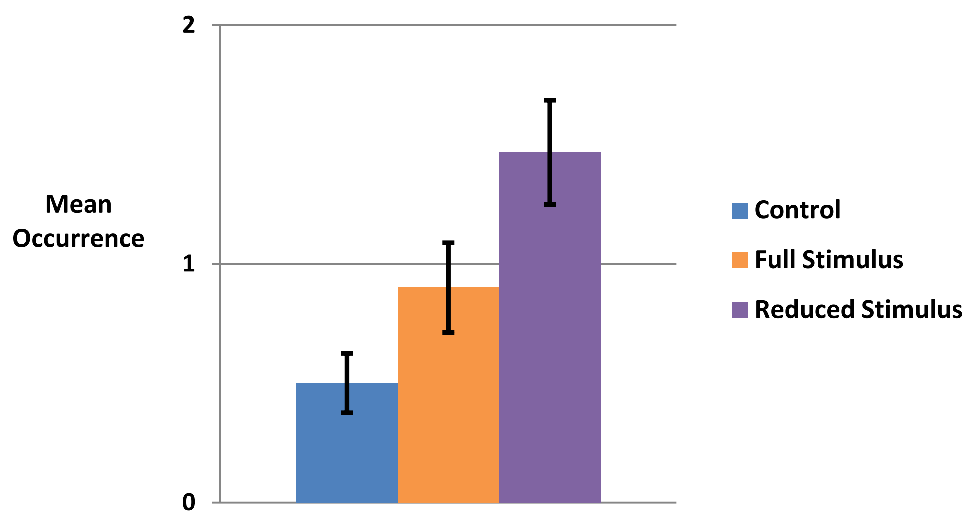

Figure 4.4: Mean occurrences of the previously-defined rising and falling gaze orientation pattern per participant for each experiment group. Standard error included.

4.2 Mean Participant Head Orientation Relative to POI Per Group

In Figure 4.5, Full Stimulus Group shows the most attentive gaze ($\bar{x} = 40.77$ degrees, $s = 8.18$) of the three groups. The Control Group performed slightly better ($\bar{x} =$

42.53 degrees, s = 11.69) than the Reduced Stimulus Group ($\bar{x}$ = 43.35 degrees, s = 11.87). One-way ANOVA was used to analyze the mean angle difference between the participants' gaze and POIs. The analysis showed no significant difference in gaze angle performance ($p > 0.05$) among the three groups [$F(2, 27) = 0.15$, $p = 0.86$].

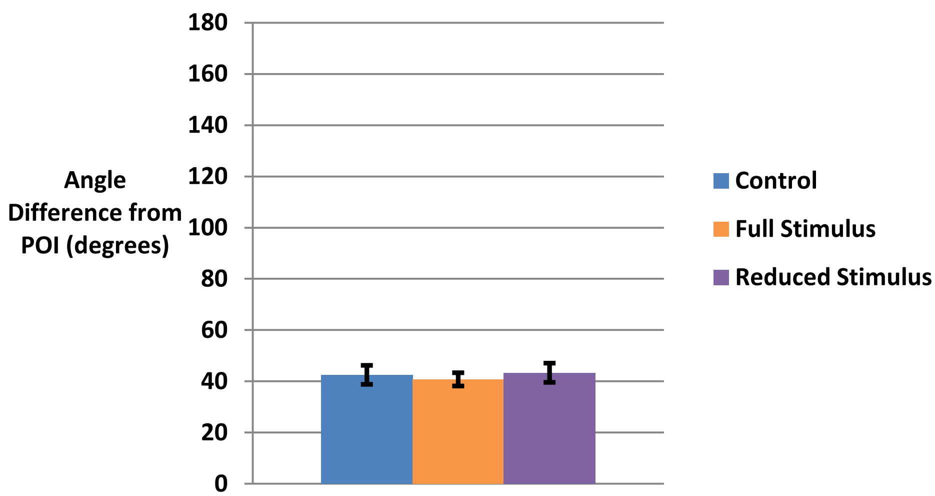

Figure 4.5: Mean participant gaze angle difference from POI per group. Lower values correspond to more attentive. Standard error included.

4.3 Mean Participant Eye Gaze Accuracy Per Group

The mean percentage of sample points when the viewer's eye gaze was within 8 degrees of the POI was calculated for each experiment group. Figure 4.6 shows the Full Stimulus Group performed better ($\bar{x}$ = 17.11, s = 7.74) than the Control Group ($\bar{x}$ = 16.44, s = 6.67) and the Reduced Stimulus Group ($\bar{x}$ = 14.39, s = 8.98). One-way ANOVA showed the difference in means was not significant [$F(2, 27) = 0.33$, $p = 0.73$].

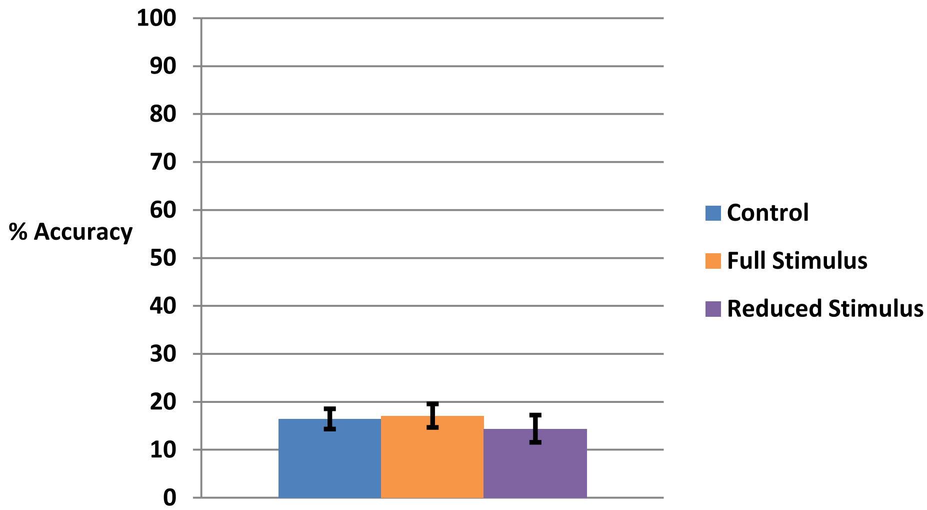

Figure 4.6: Mean eye gaze accuracy relative to the POI for each group. Higher values correspond to more favorable performance. Standard error included.

4.4 Mean Participant SSQ Scoring Per Group

The Simulator Sickness Questionnaire (SSQ) is a widely accepted standard for reporting symptoms by participants using a VR system. The SSQ is scored by dividing responses into three weighted subscores and one weighted total score, *TS*. The three subscores are *N*, nausea-related symptoms (general discomfort, increased salivation, sweating, nausea, difficulty concentrating, stomach awareness, and burping), *O*: oculomotor symptoms (general discomfort, fatigue, headache, eye strain, difficulty focusing, difficulty concentrating, and blurred vision), and *D*: disorientation-related symptoms (difficulty focusing, nausea, fullness of the head, blurred vision, dizzyness with eyes open, dizzyness with eyes closed, and vertigo) [21].

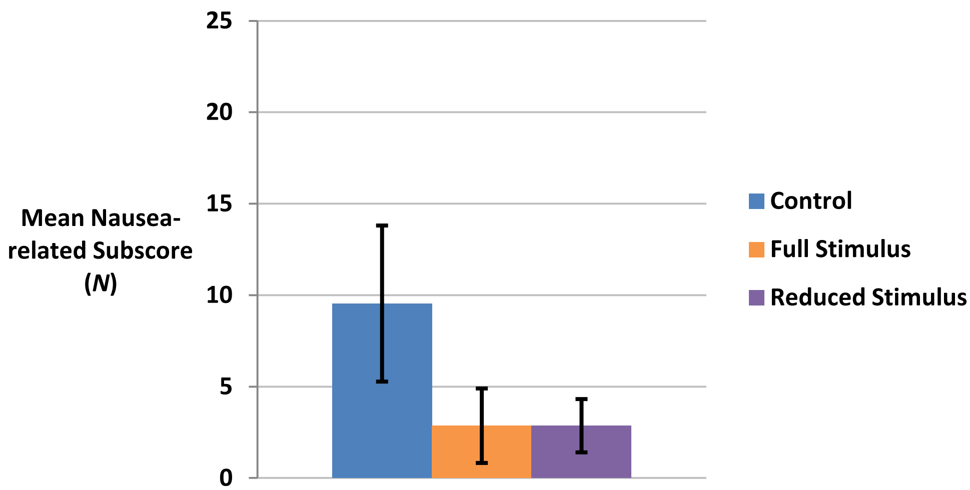

Figure 4.7: Mean participant nausea-related SSQ subscores by experiment group. Lower values correspond to less severe nausea related symptoms. Standard error included.

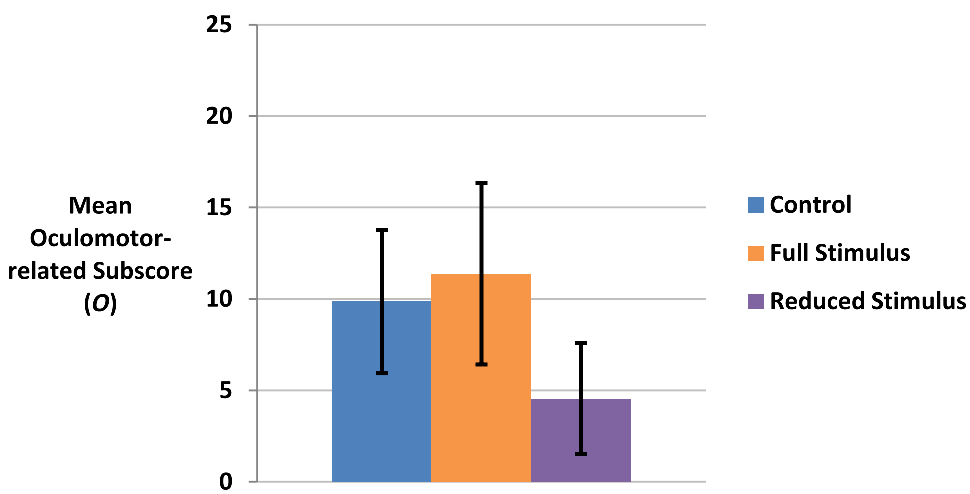

Figure 4.8: Mean participant oculomotor-related SSQ subscores by experiment group. Lower values correspond to less severe oculomotor-related symptoms. Standard error included.

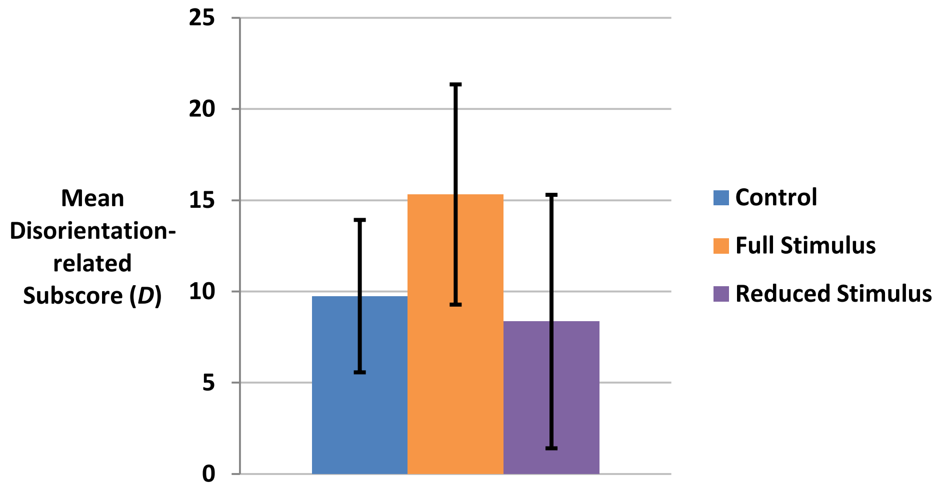

Figure 4.9: Mean participant disorientation-related SSQ subscores by experiment group. Lower values correspond to less severe disorientation-related symptoms. Standard error included.

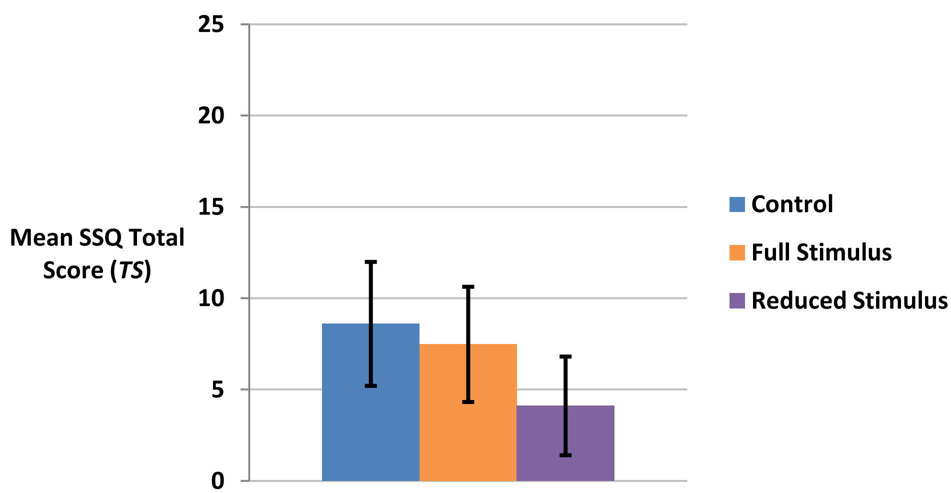

Figure 4.10: Mean participant SSQ total scores by experiment group. Lower values correspond to less severe symptoms. Standard error included.

Figures 4.7 through 4.10 show mean self-reported SSQ subscores and total scores per experiment group. *N* was highest in the Control Group ($\bar{x}$ = 9.54, s = 13.49), *O* was highest in Full Stimulus Group ($\bar{x}$ = 11.37, s = 4.96), *D* was highest in Full Stimulus Group ($\bar{x}$ = 15.31, s = 6.03), and *TS* was highest in Control Group ($\bar{x}$ = 8.60, s = 3.39). One-way ANOVA tests showed that the differences in group scores was not significant [$F_N(2, 27) = 1.82$, $p_N = 0.18$], [$F_O(2, 27) = 0.78$, $p_O = 0.47$], [$F_D(2, 27) = 0.40$, $p_D = 0.68$], [$F_{TS}(2, 27) = 0.57$, $p_{TS} = 0.57$].

4.5 Mean Participant VE Comprehension Score Per Group

Post-study VE comprehension questionnaire scores were recorded for each participant. Mean scores were calculated for each group. Figure 4.11 shows that VE comprehension scores were highest for Full Stimulus Group ($\bar{x}$ = 76.67, s = 23.83). Scores in the Reduced Stimulus Group ($\bar{x}$ = 61.67, s = 29.45) were higher than in the Control Group ($\bar{x}$ = 56.67, s = 37.84). One-way ANOVA tests showed no significant effect on VE comprehension for the three groups [$F(2, 27) = 1.13$, $p = 0.34$].

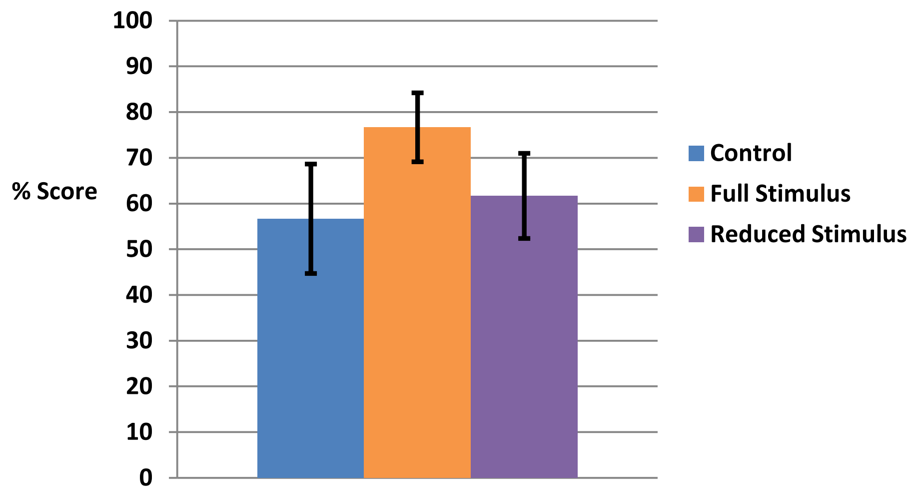

Figure 4.11: Mean VE comprehension scores per group. Higher values correspond to more favorable performance. Standard error included.

5. DISCUSSION

5.1 Discussion

Gaze patterns in the line graphs suggest that participants the Reduced Stimulus Group were reacting to the yellow color effect, turning their heads back towards the POI when the effect was detected. While these patterns also exist in the Control Group, they were significantly less frequent. These patterns suggest that the stimulus was successful in re-directing participant gaze in certain cases. It is interesting to note that higher stimulus strength did not necessarily correlate to a higher rate of gaze re-direction. Differences in individual viewing patterns might account for the Full Stimulus Group lying somewhere in-between the Reduced Stimulus Group and Control Group.

Analysis of participants' gaze performance data suggests that the solution to *holding* viewer gaze onto POIs remains elusive. The problem of holding viewer gaze could be due to several factors, such as the attention span of the participant, boredom or other psychological factors, the participant's desire to turn their head or body, the participant's level of experience or comfort with VR, and participant age. Results do not suggest that there was a learning effect as participants viewed the VEs in sequence.

The design of the POIs in this experiment may have contributed to the gaze holding problem. The POIs were stationary and did not continuously change. This design might have led to decreased viewer interest.

Eye tracking data revealed that POIs, bounded by the 8-degree "dead zone" radius, rarely fell into viewers' macular vision range [23]. Eye tracking sensor error due to the HMD shifting on participants' faces, blinking, and hardware limitations might have contributed to lower overall ocular attentiveness. Recording eye gaze angle difference from POIs might have been a more sufficient data recording method, but because eye saccades are much quicker than head movements [24], a much higher data sample frequency would have been required. Such a high rate of sampling may have adversely affected the frame rate of the VE.

Mean SSQ scores were found to be lower for the Full Stimulus and Reduced Stimulus Groups than for the Control Group. This disparity could have been influenced by participants' individual levels of experience with VR. Different individuals might also have different definitions of "slight", "moderate", and "severe" symptoms. It is worth noting that the mean SSQ total score of the entire sample population ($\bar{x} = 6.73$, $s = 9.64$) was low compared to the maximum possible SSQ total score, 179.52. No single symptom on any participant's SSQ received a rating of 3, or "severe".

Analysis of post-study VE comprehension questionnaires showed no statistically significant difference in mean group scores. However, it is encouraging that the difference in mean scores between Full Stimulus Group ($\bar{x} = 76.67$, $s = 23.83$) and Control Group ($\bar{x} = 56.67$, $s = 37.84$) was the difference between "C" and "F" letter grades. SSQ and VE comprehension results suggest that yellow color effect did not significantly distract viewers.

5.2 Implications

The stimulus tested in this experiment has potential as an accessible and customizable gaze direction technique without the need for extra objects as distractors. It could be applied to virtual classrooms, training simulators, narrative immersive animations, or any application requiring viewer attentiveness to POIs. It can be recreated in any VR software that supports rendered image processing. The stimulus has potential to be adapted to a more art-directed image effect that gradually changes the rendered image as the viewer looks away. By testing the stimulus at both full strength and at 63% strength, I have shown that the color effect is scaleable to some degree. The effect's maximum strength can be modified by the developer to preserve more of the VE's original colors. After analyzing the head orientation angle data graphs, it is encouraging to observe that testing the stimulus at a reduced strength and thereby preserving more of the VE's original color showed more instances of gaze re-direction versus the control group than testing at full stimulus strength. While it remains a challenge to hold viewer gaze, this type of gaze direction stimulus may be useful if strategically "activated" a few seconds before important happenings in the VE.

5.3 Limitations

This experiment is limited by its small sample population size relative to the actual population of sighted adults with normal vision. A larger sample population might allow for participants to be placed in sub-groups based on self-reported levels of experience with electronic games and VR. Having participants sit at a desk was more inclusive to volunteers who may not have been able to stand, but it may have encouraged gaze behavior to be constrained to straight ahead of the viewer.

6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

A novel method of VR gaze direction based on a dynamic real-time yellow color effect has been presented. It can be concluded that the results of the experiment support the hypothesis H1: that the stimulus would successfully re-direct viewer gaze. However, the stimulus did not appear to improve overall gaze performance. Therefore, it can be concluded that the study results do not support the hypothesis H2. Results appear to support hypothesis H3; therefore it can be concluded that the color effect did not significantly increase SSQ scores within the sample population. Finally, it can be concluded that the color effect did not significantly improve VE comprehension scores versus the Control Group.

6.2 Future Work

This experiment has been an encouraging start to exploring the potential of dynamic, real-time color effects as VR gaze direction devices. Future studies will include more participants, with more dynamic POIs that move or have continuous actions. Multiple POIs that each require the viewer's attention at certain times could also be additions to future work. To evaluate how the stimulus affected participants' overall experience, subjective responses/comments could be provided by participants. They could also help to understand if viewers reacted to the stimulus because something changed visually, or because the hue of the color effect specifically acted as negative reinforcement. There is great potential to test other hues such as red, yellow, orange, and violet as color effects in future experiments. Furthermore, a hue change could be combined with changes in saturation, value, or contrast to create a more art-directed image effect. Future experiments on this kind of visual stimulus could also incorporate audio cues.

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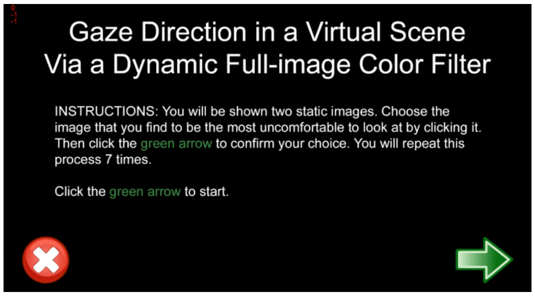
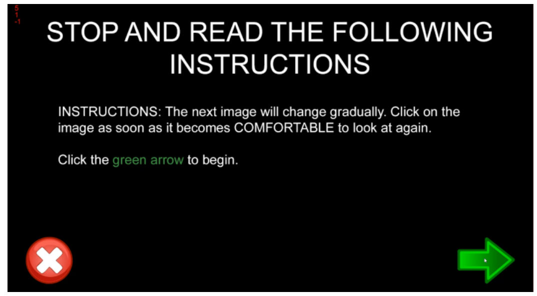
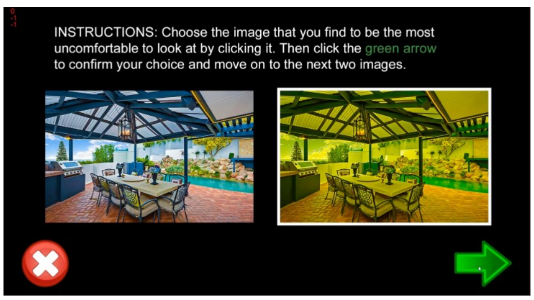
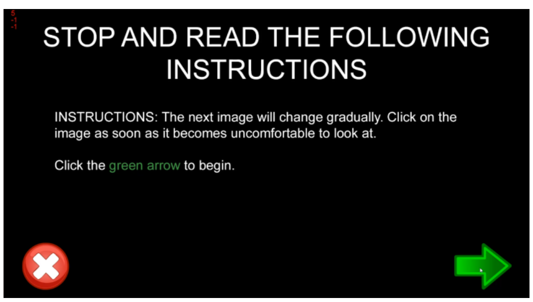
APPENDIX

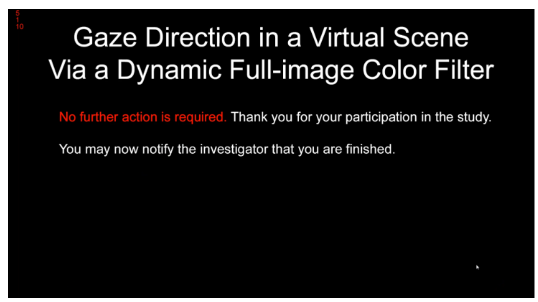
The following images were taken from the application used in the pilot study:

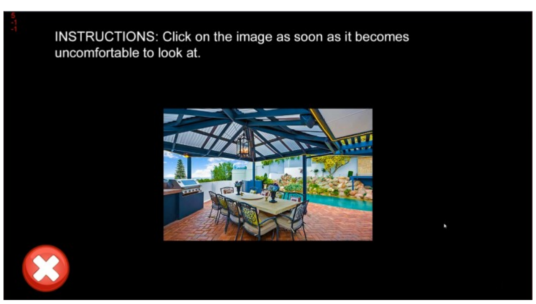












Prior to beginning the experiment, each participant was asked to complete the following pre-study questionnaire:

CIRCLE ONE: How experienced are you with electronic games (video games, mobile games, computer games, etc.)?

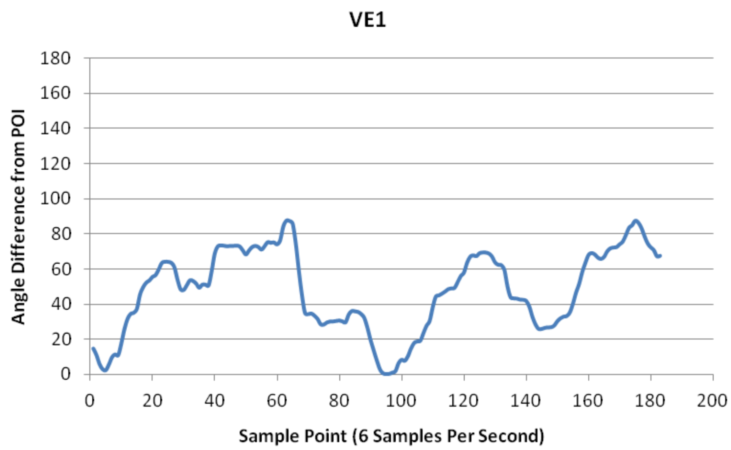
- Not experienced
- Somewhat experienced
- Very experienced

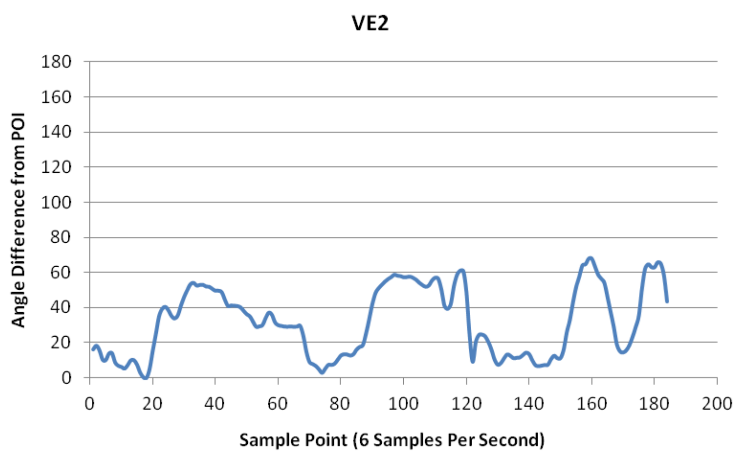
CIRCLE ONE: How experienced are you with virtual reality?

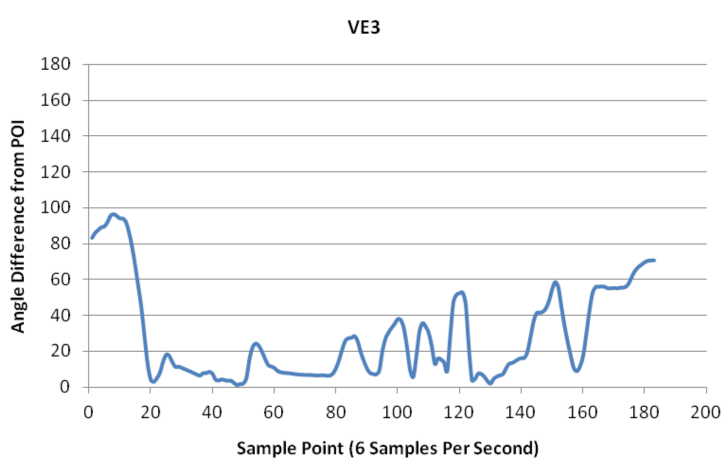
- Not experienced
- Somewhat experienced
- Very experienced

Head Orientation Angle Relative to POI Graphed Over Time

Participant 2017-11-06_01 Group: Control







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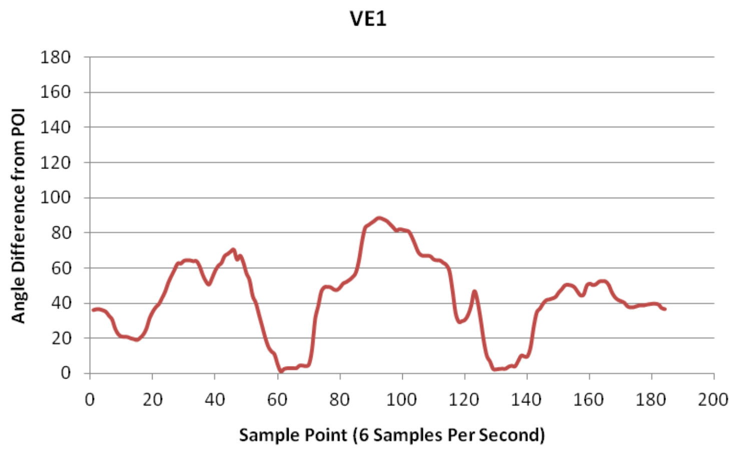

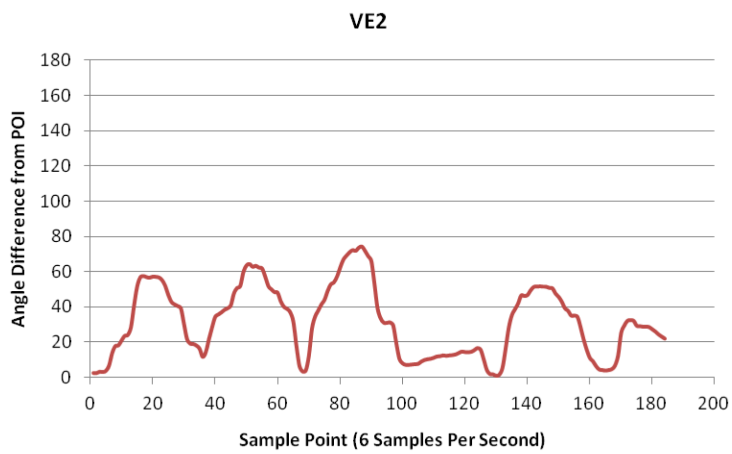

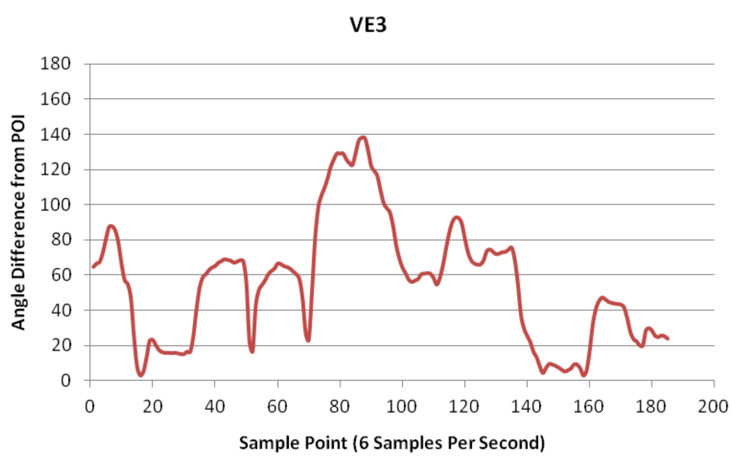

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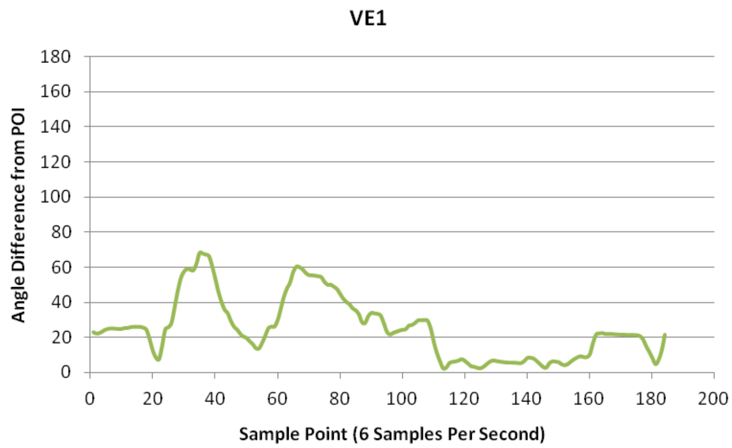

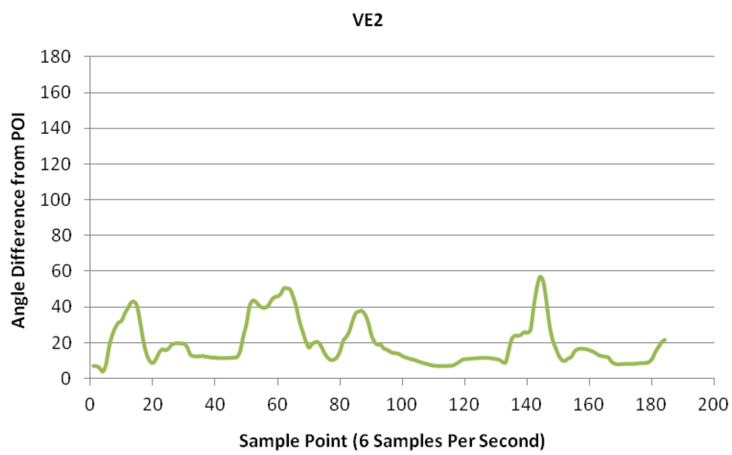

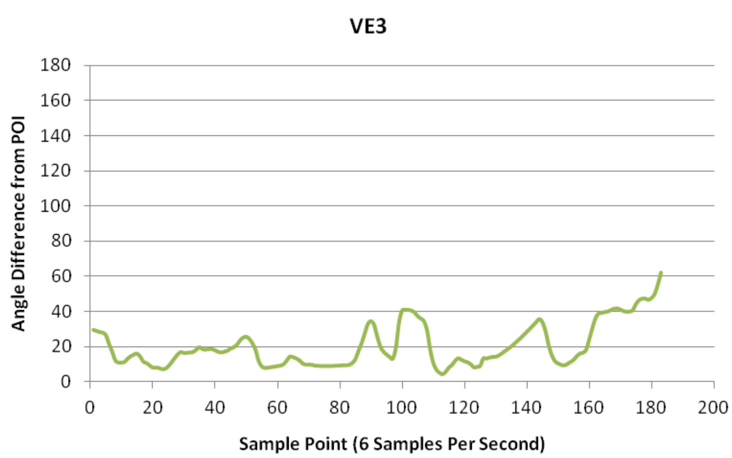

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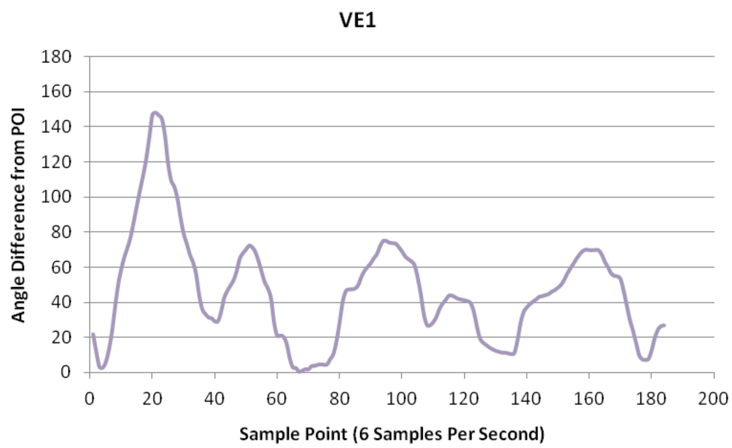

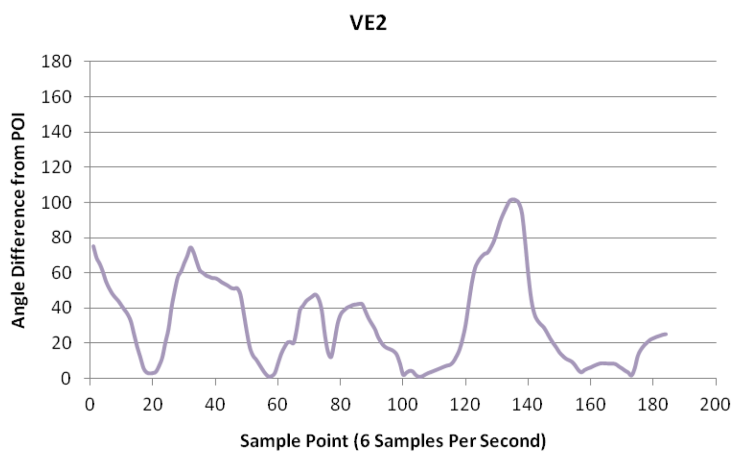

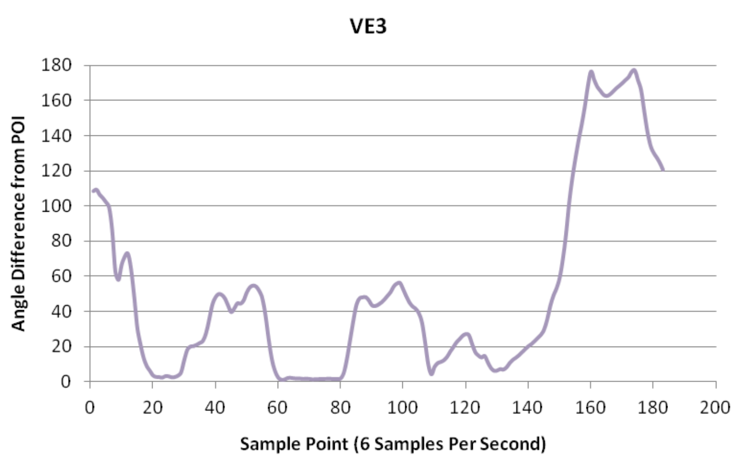

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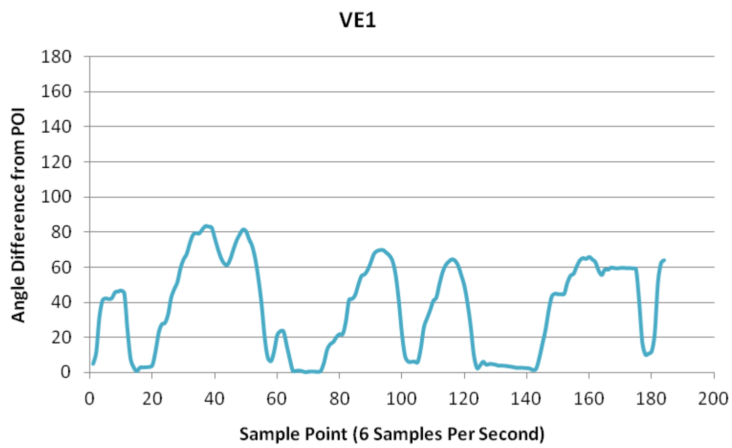

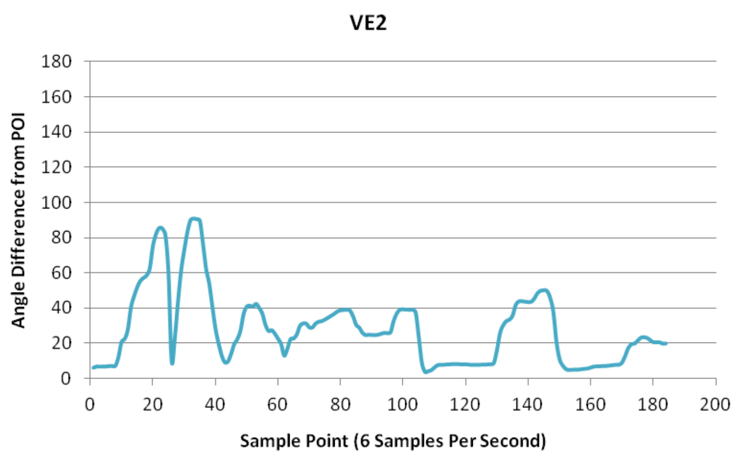

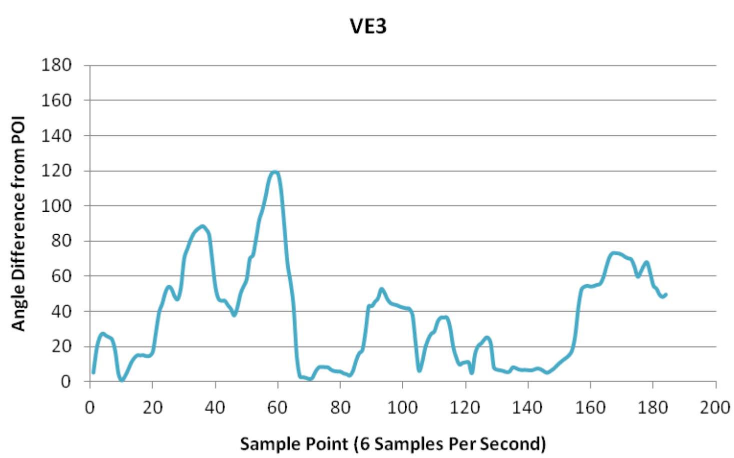

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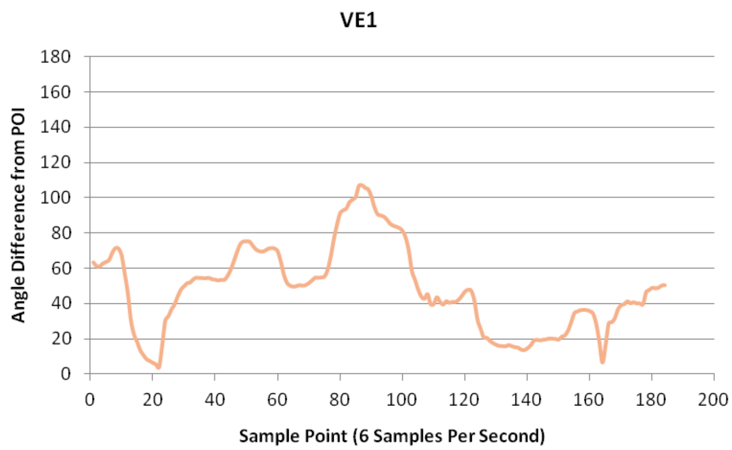

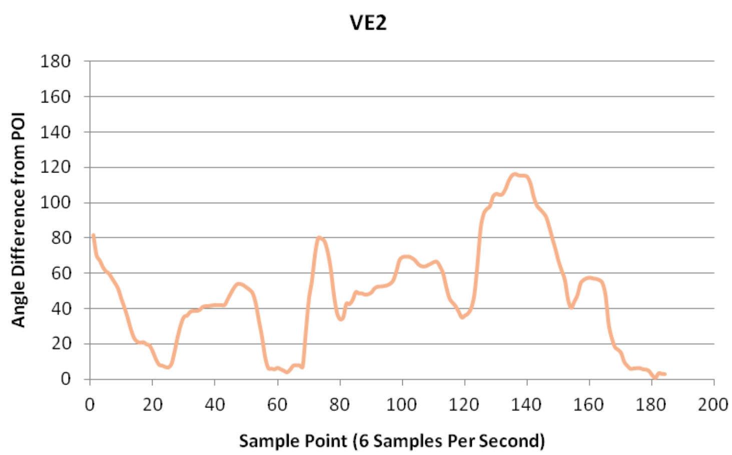

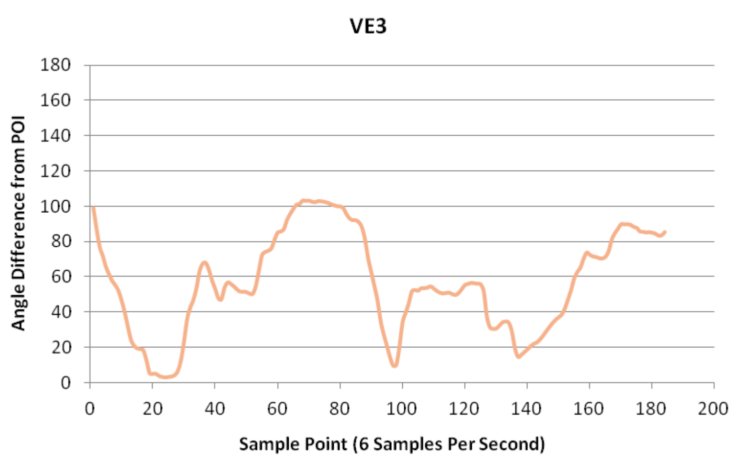

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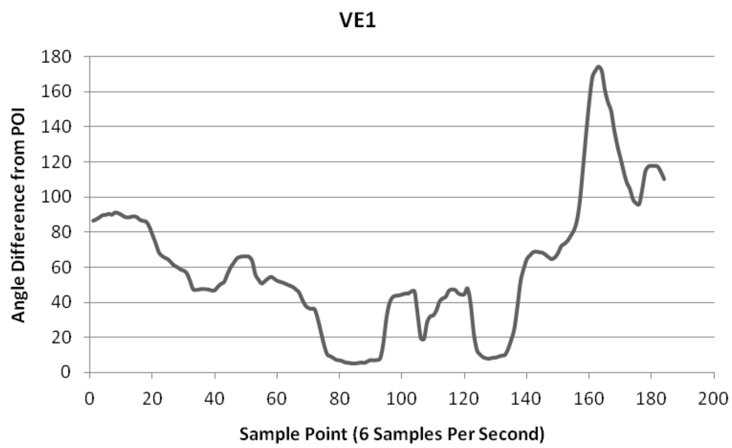

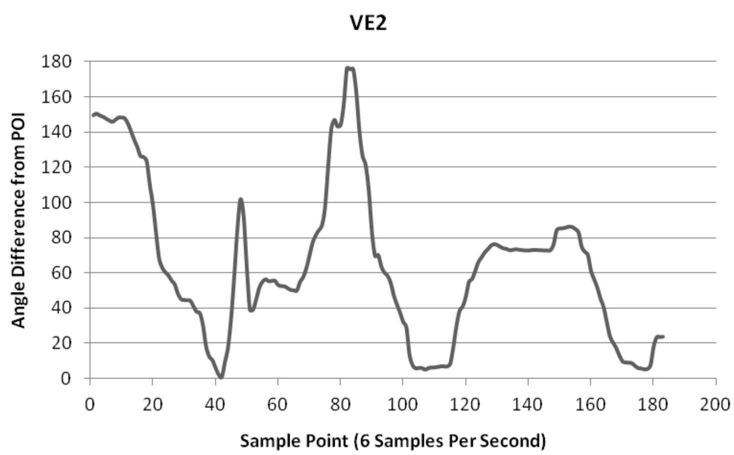

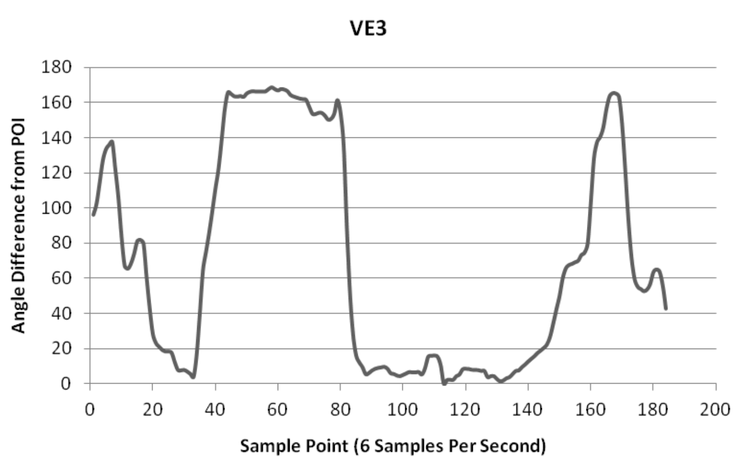

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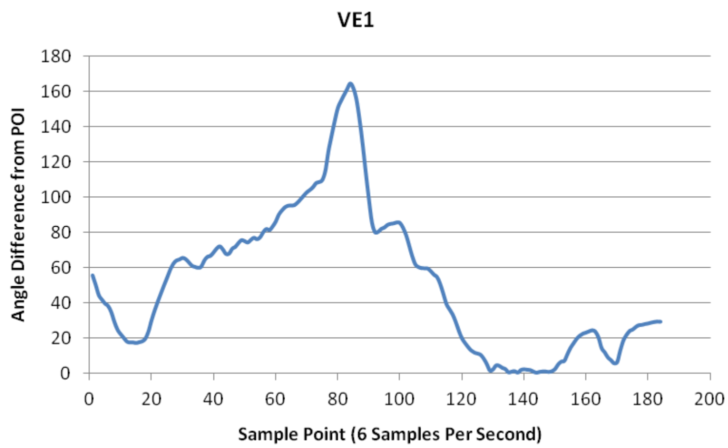
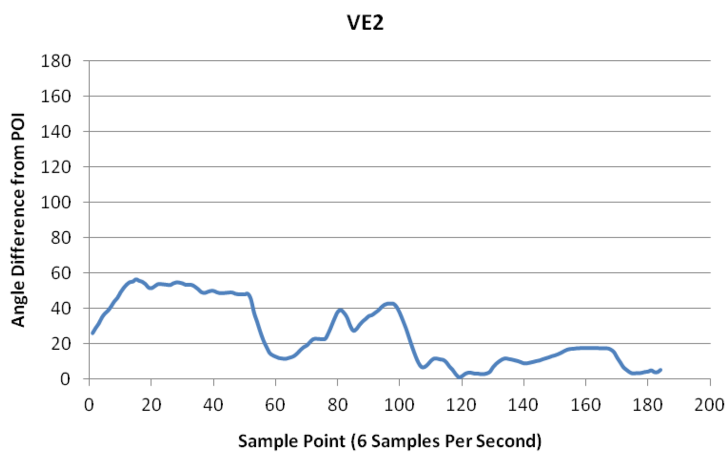
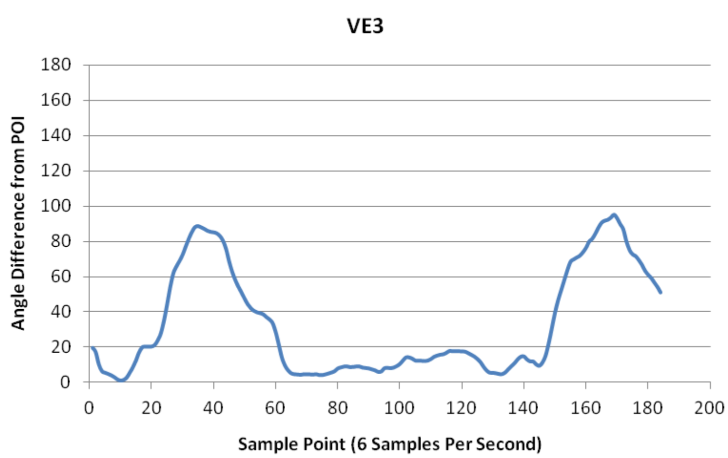
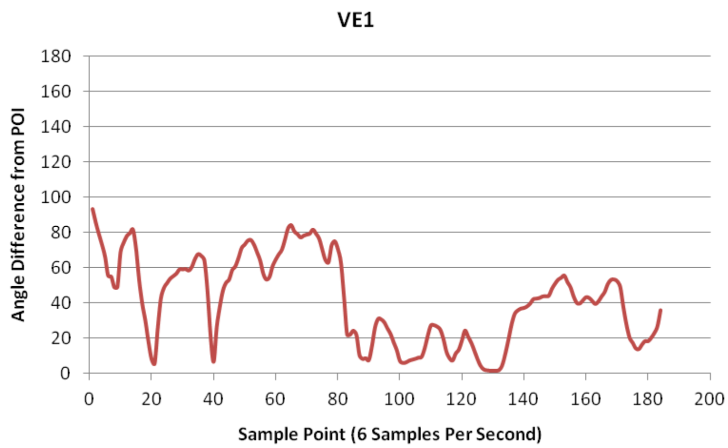
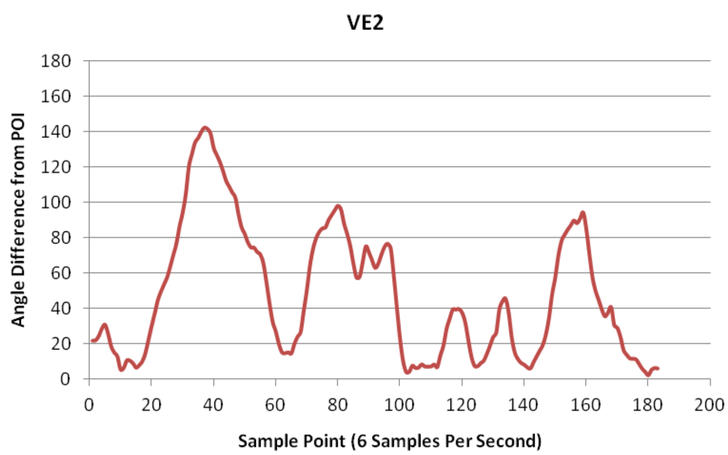


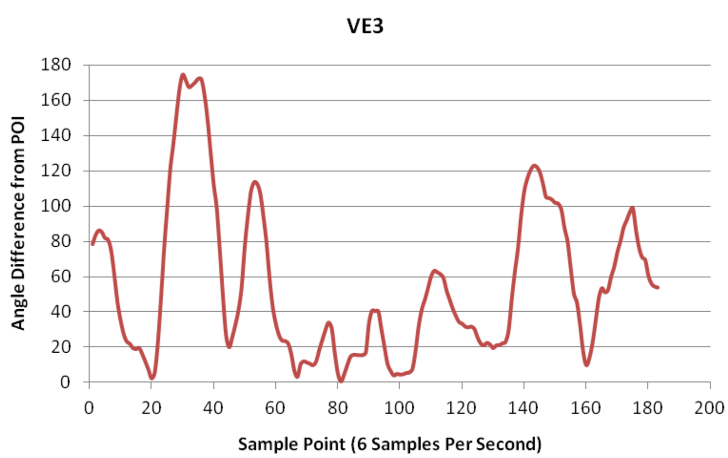




Participant 2017-12-04_01 Group: Control







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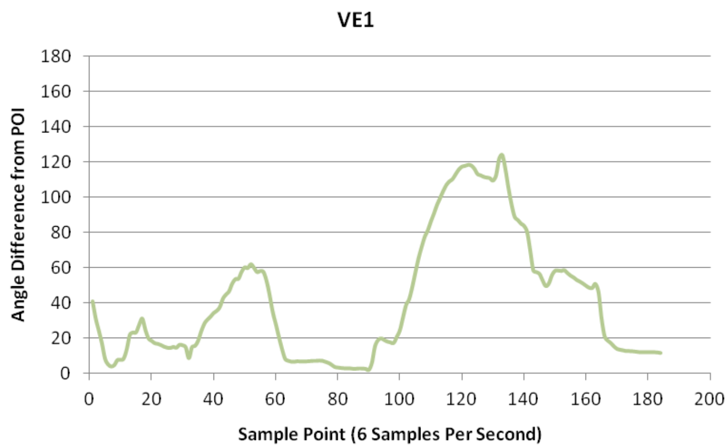

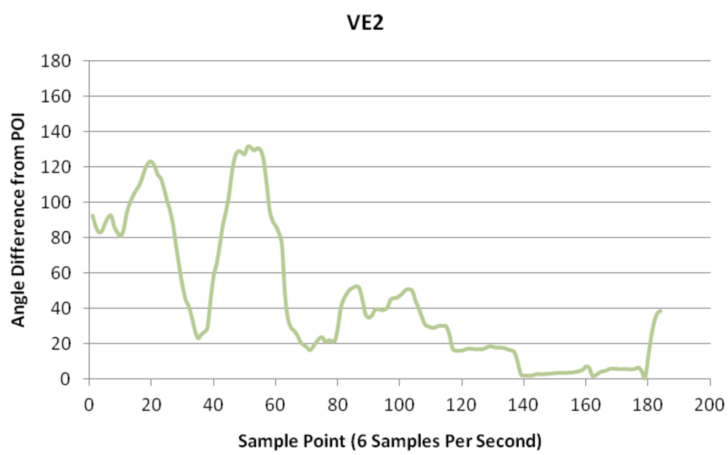

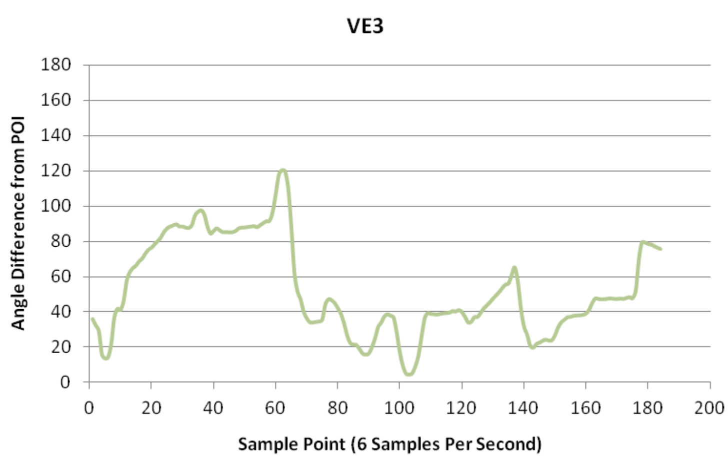

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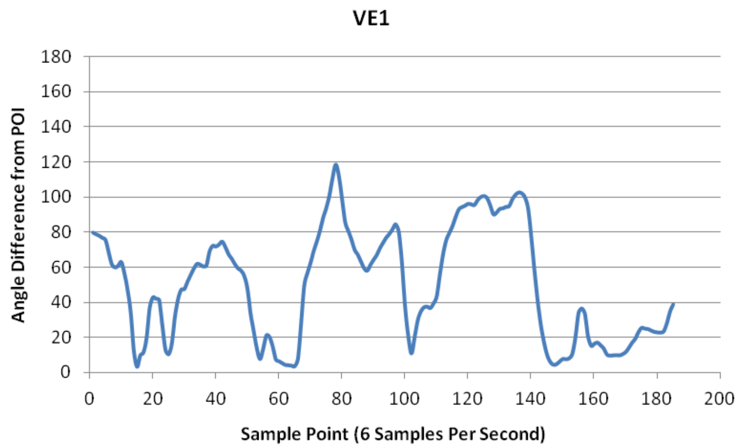

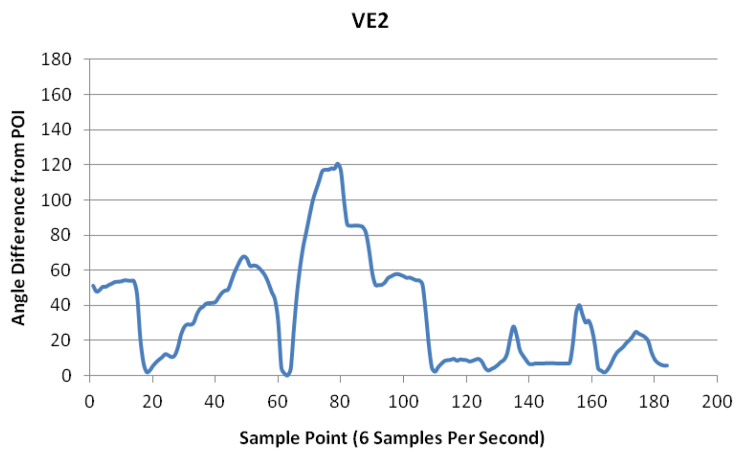

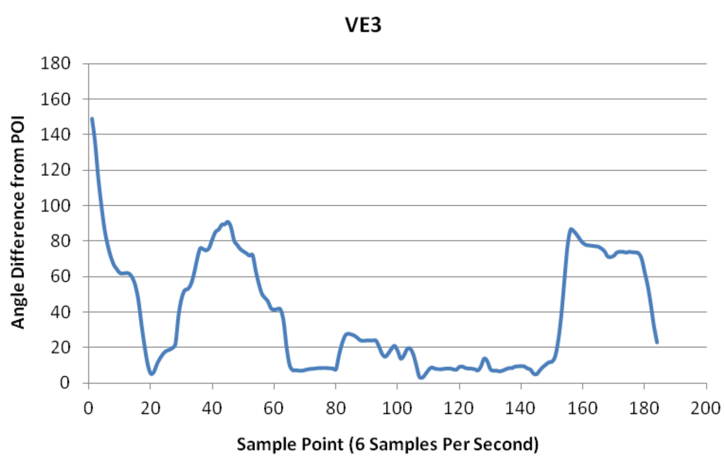

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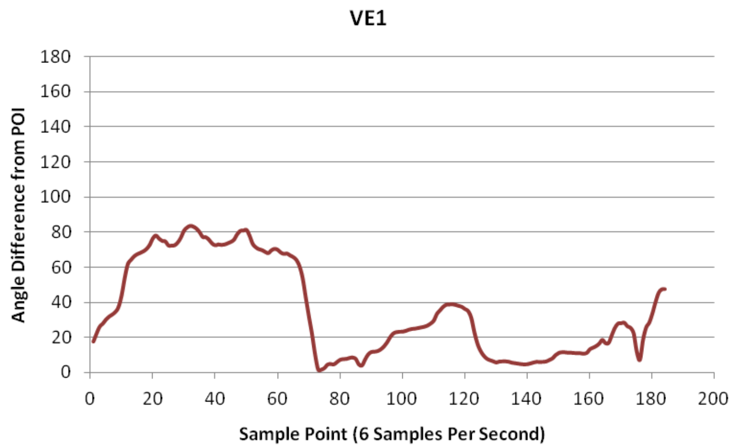
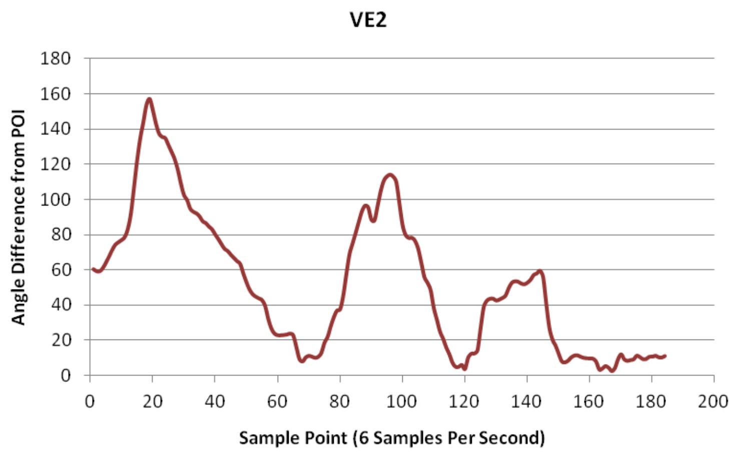
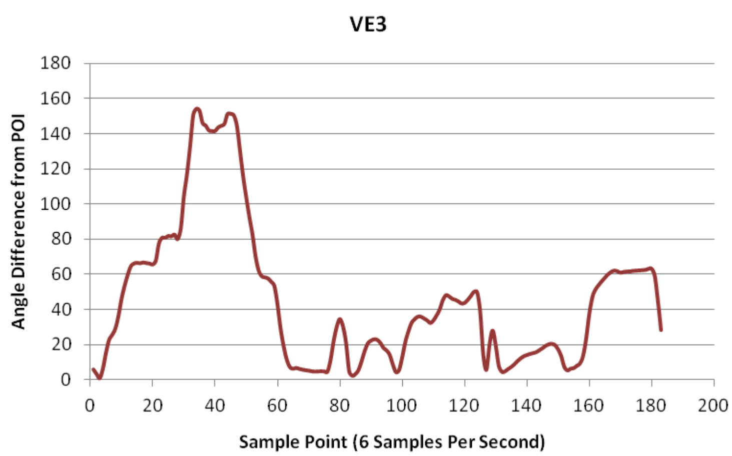
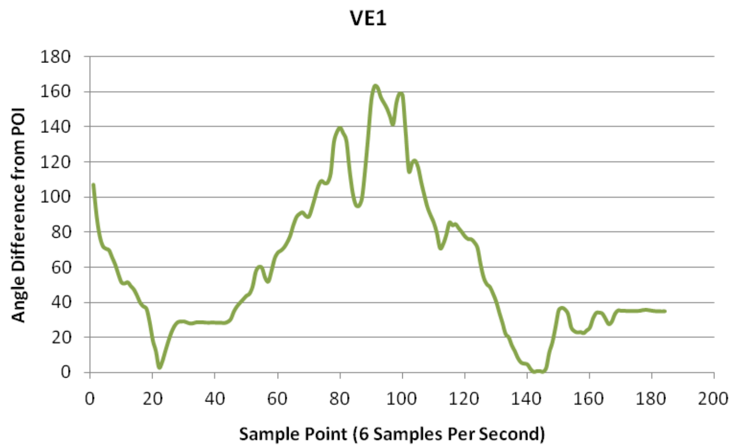
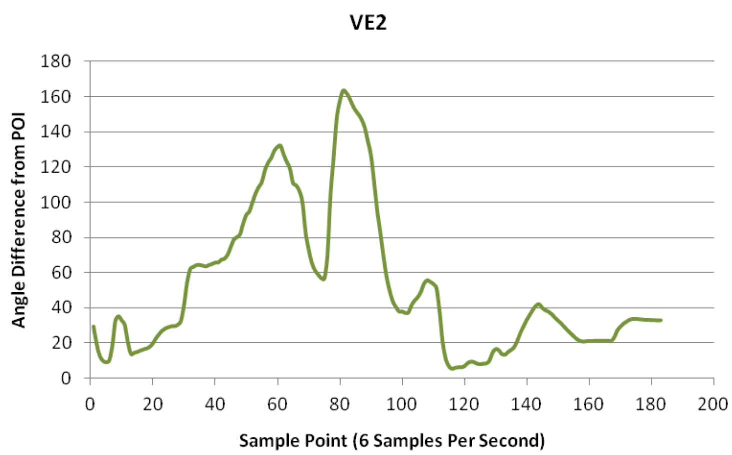


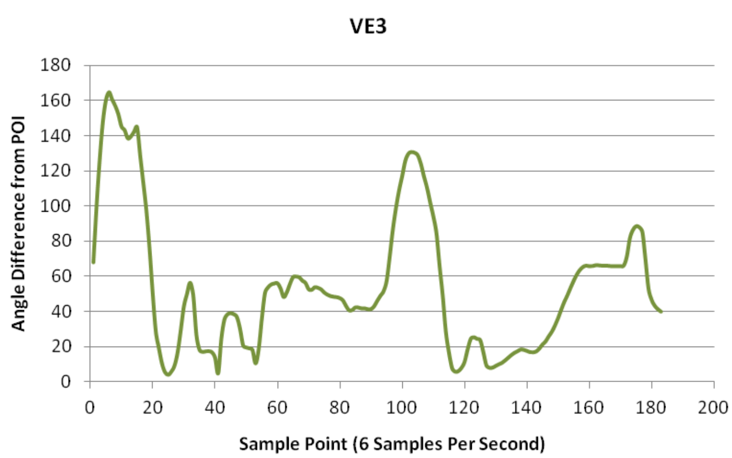




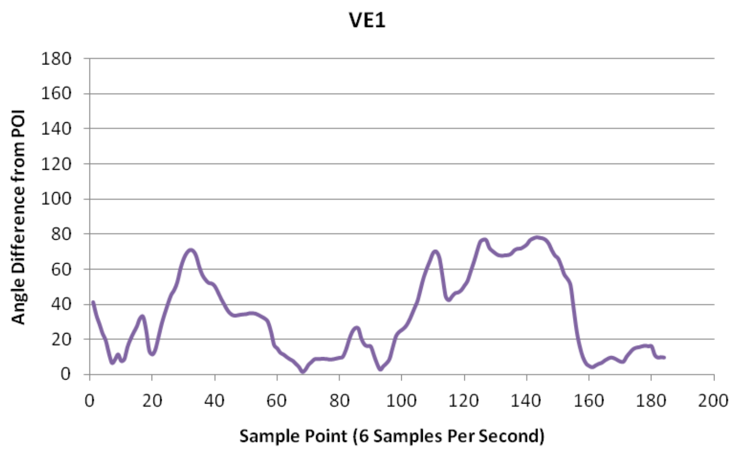
Participant 2017-10-13_01 Group: Full Stimulus

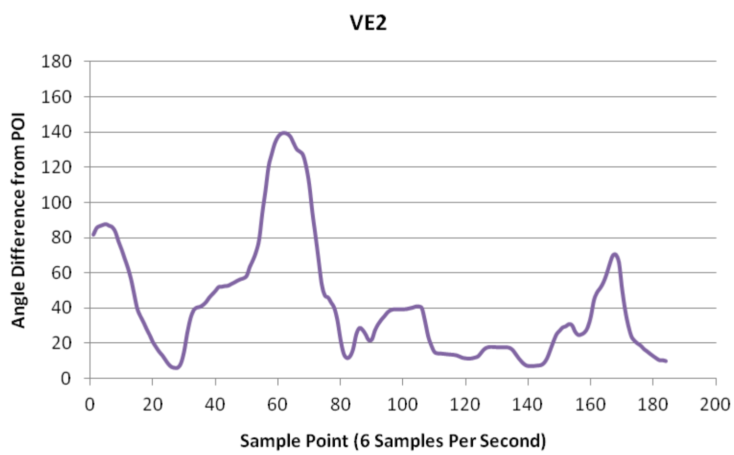


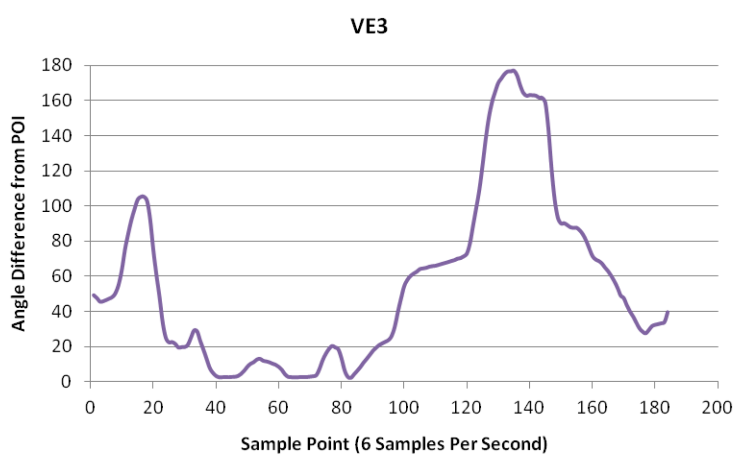




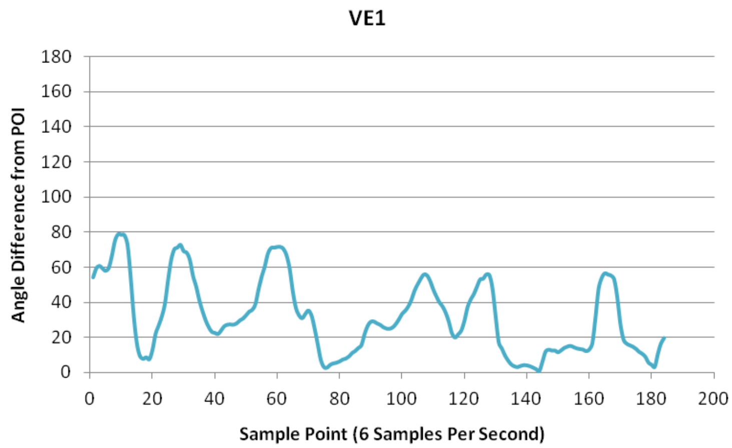
Participant 2017-10-13_02 Group: Full Stimulus

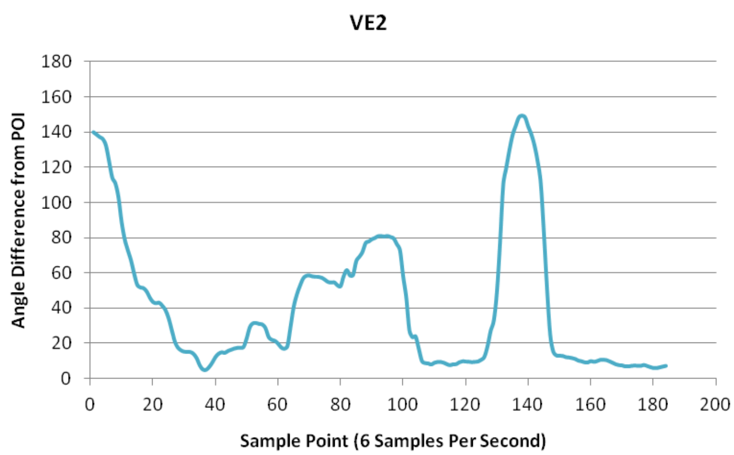


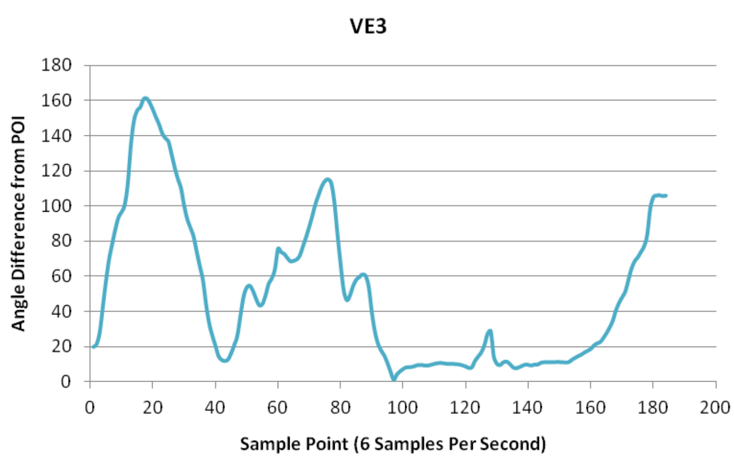




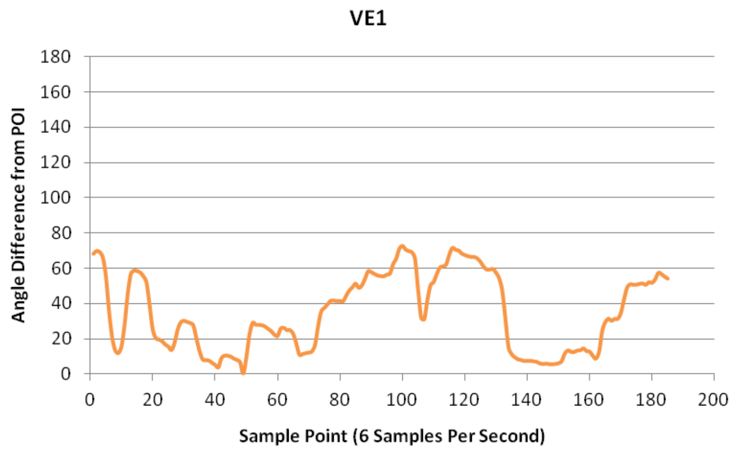
Participant 2017-10-13_03 Group: Full Stimulus

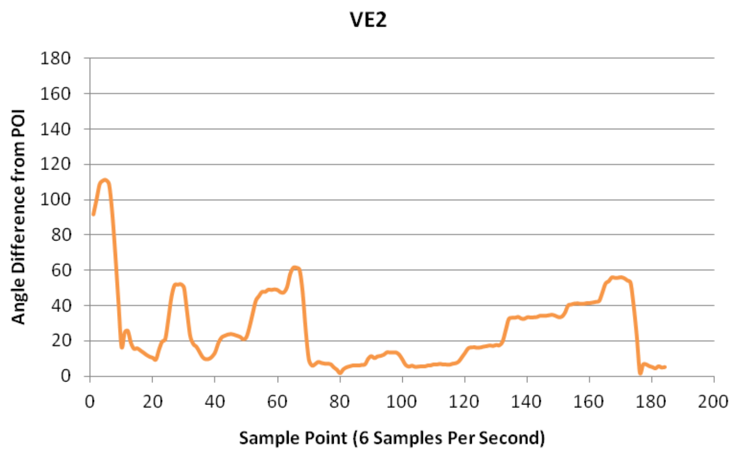


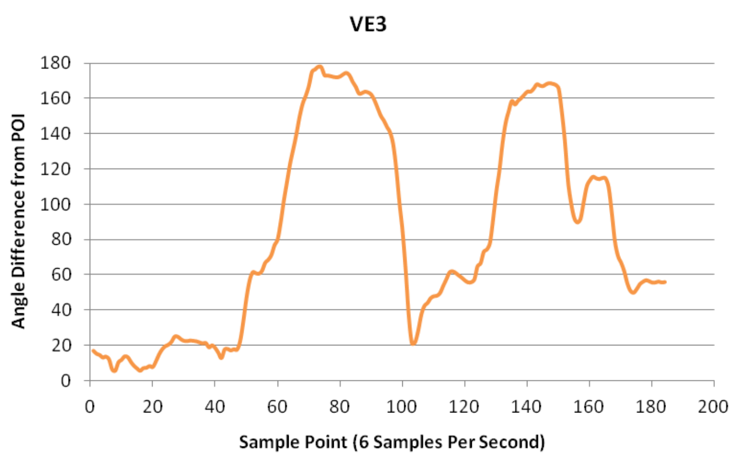




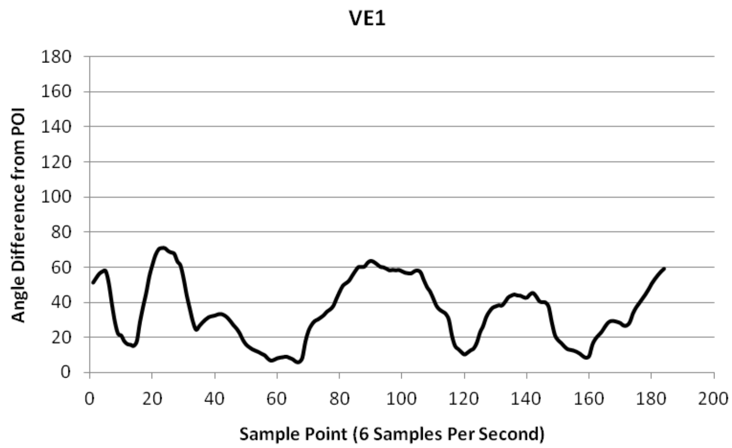
Participant 2017-10-13_04 Group: Full Stimulus

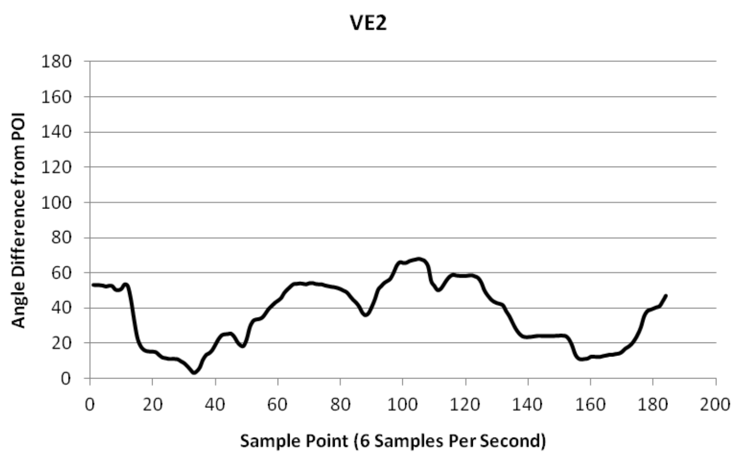


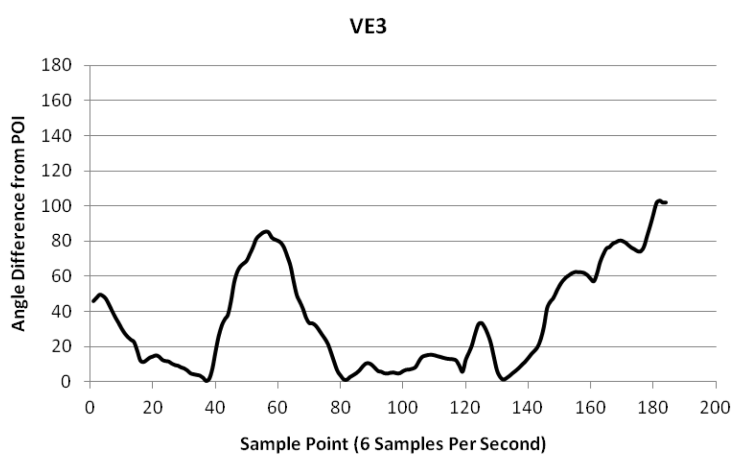




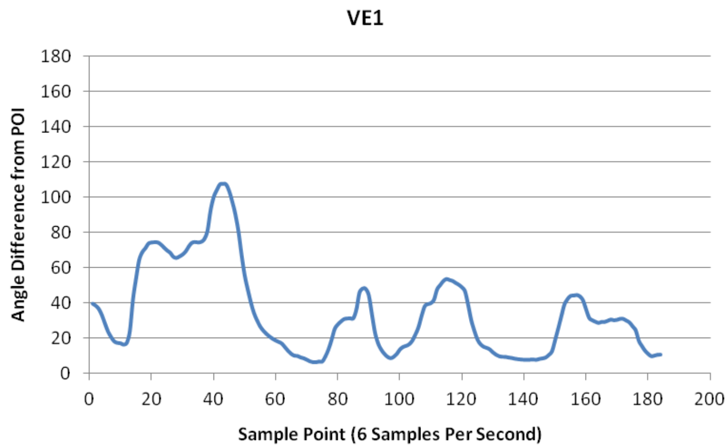
Participant 2017-11-06_04 Group: Full Stimulus

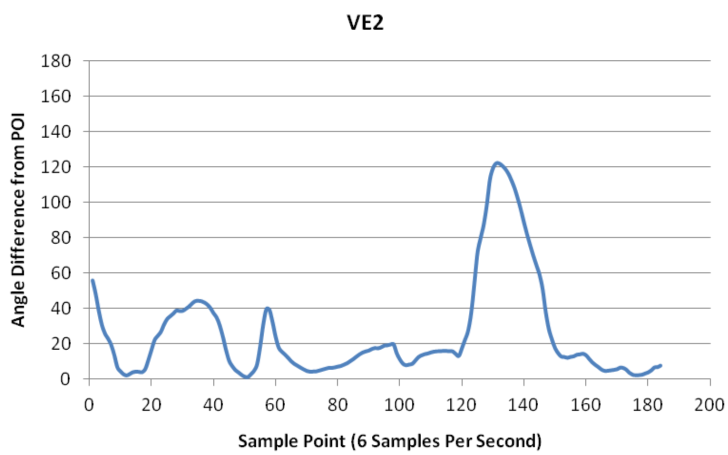


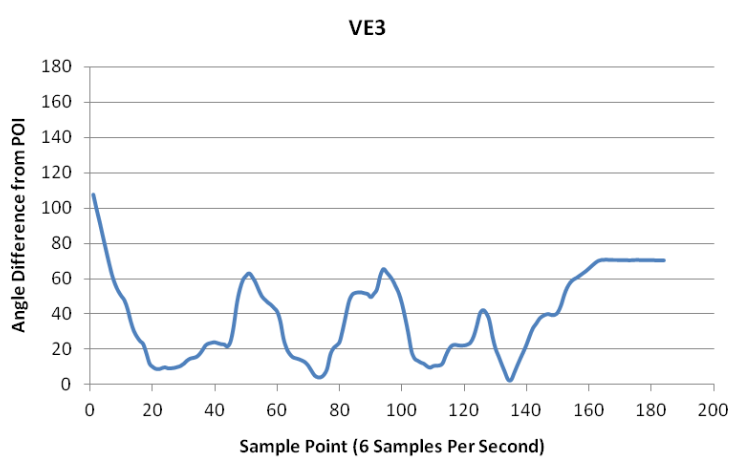




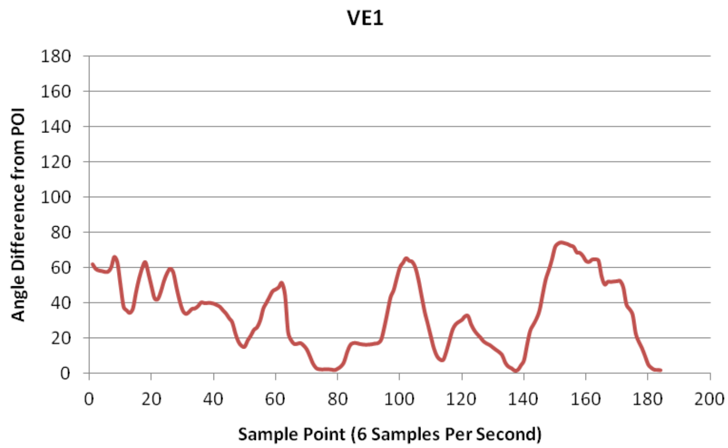
Participant 2017-11-08_01 Group: Full Stimulus

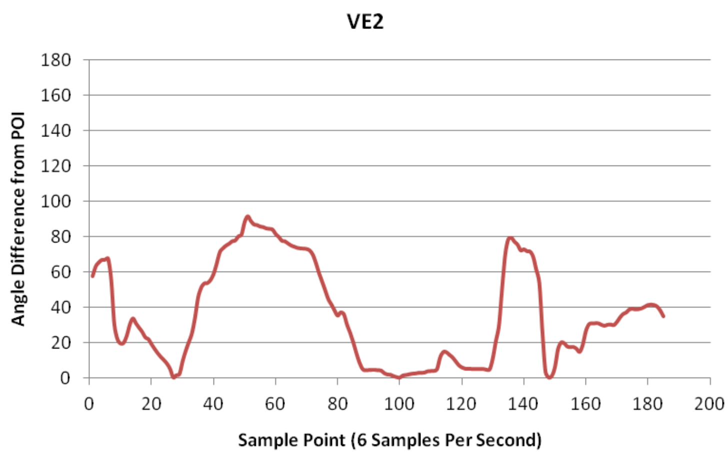


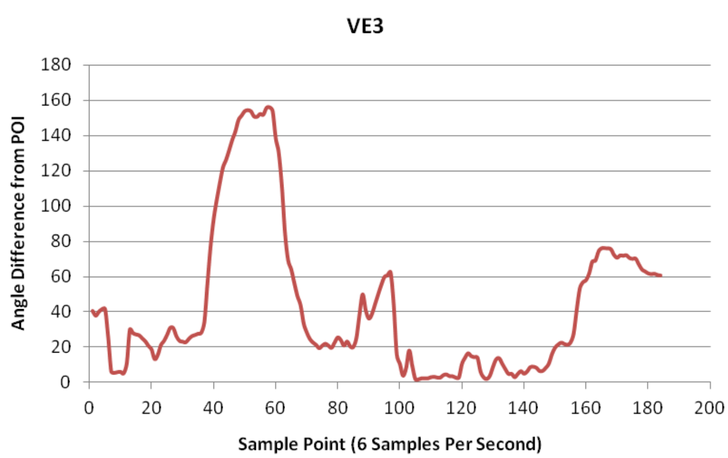




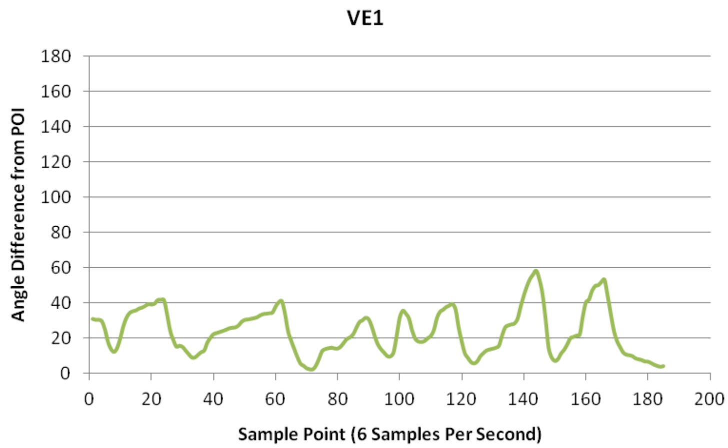
Participant 2017-11-26_01 Group: Full Stimulus

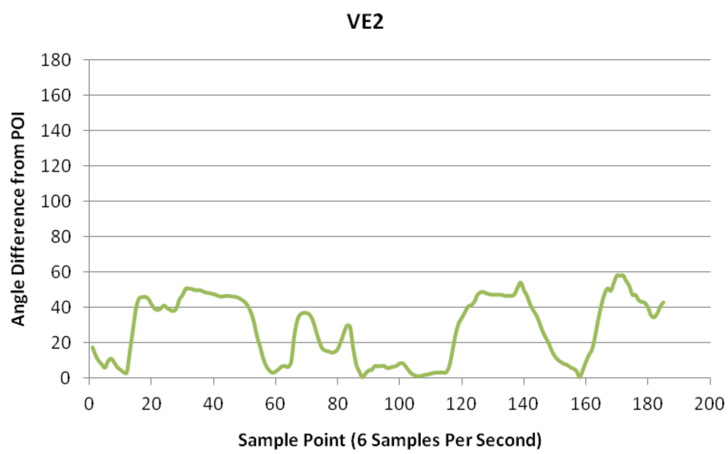


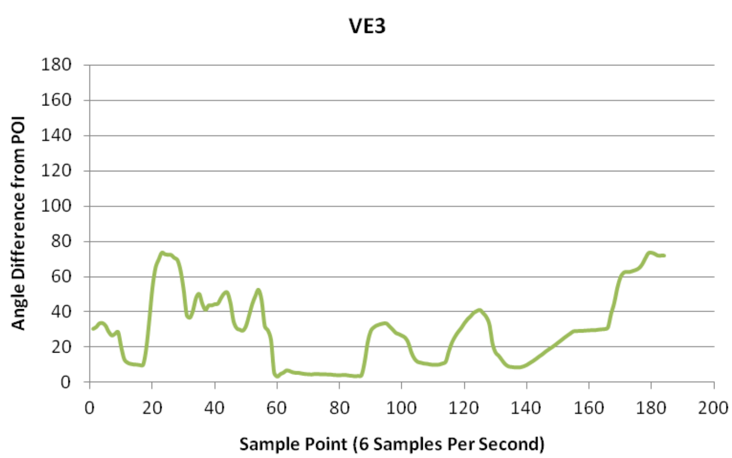




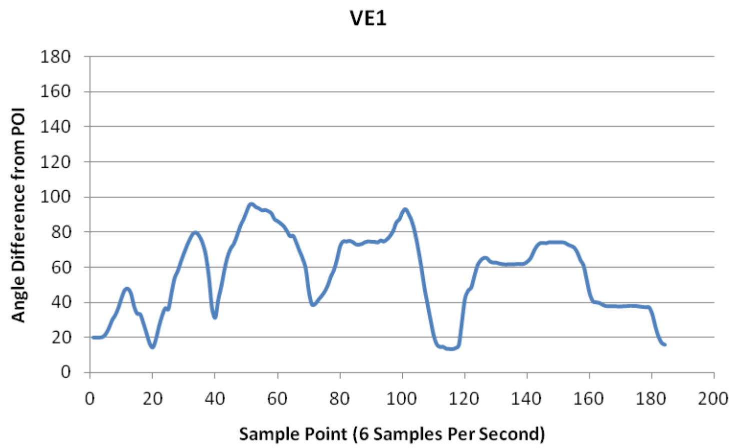
Participant 2017-11-29_02 Group: Full Stimulus

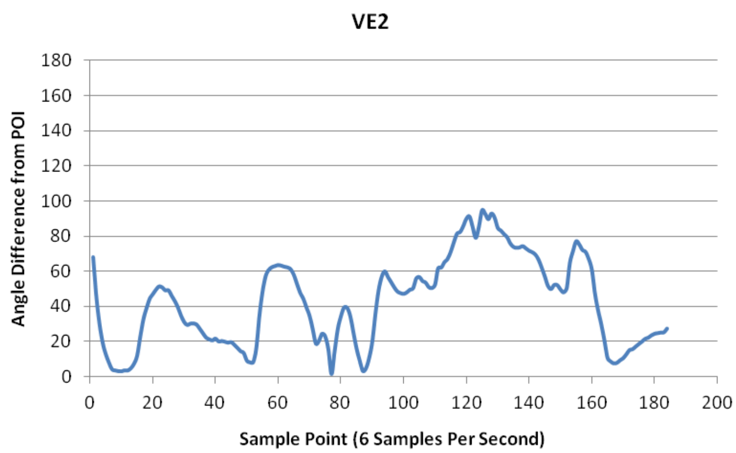


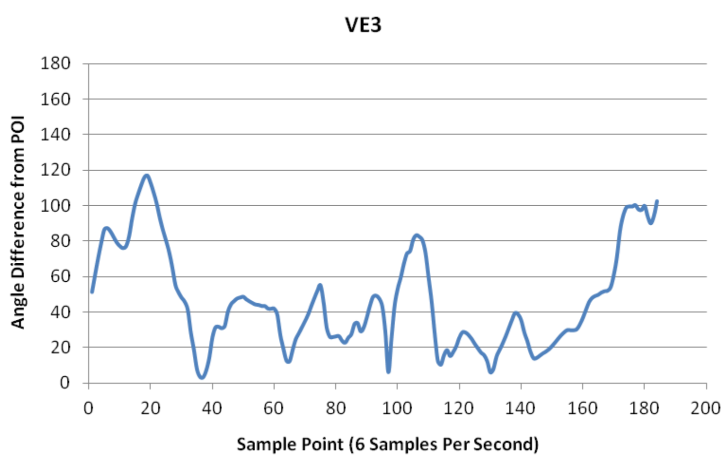




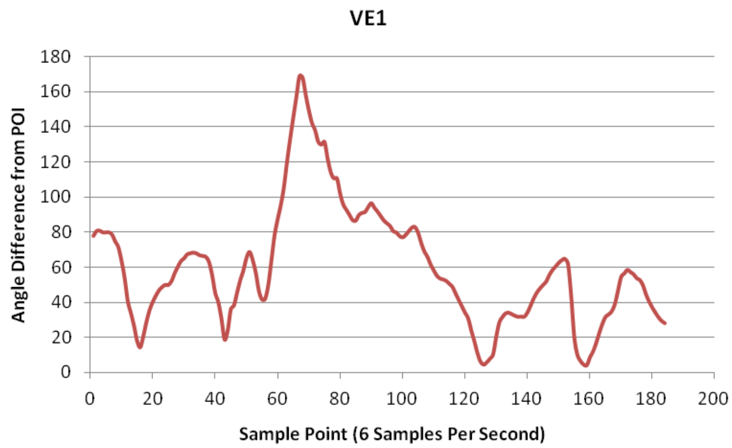
Participant 2017-10-10_01 Group: Reduced Stimulus

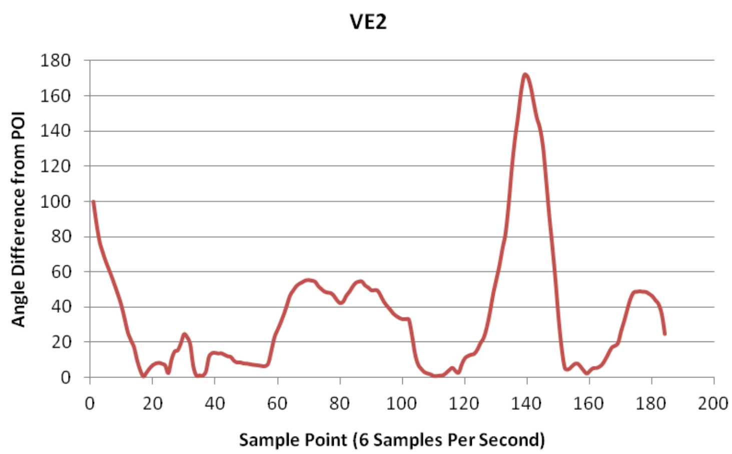


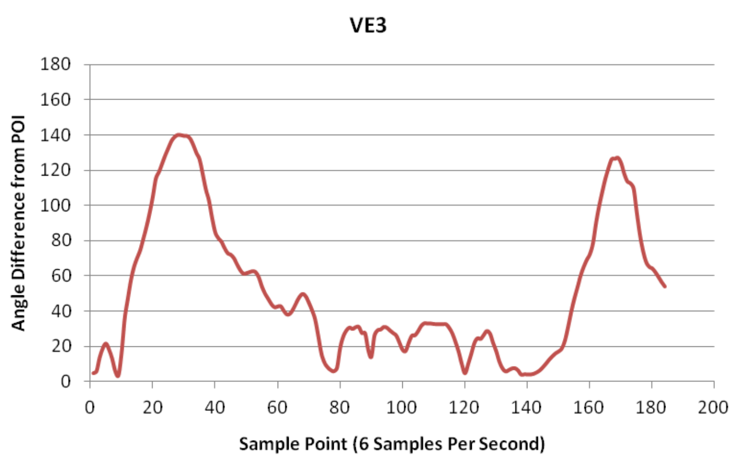




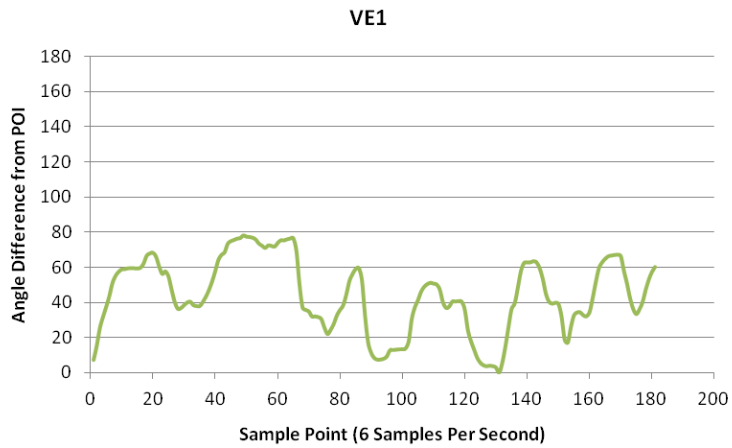
Participant 2017-11-08_02 Group: Reduced Stimulus

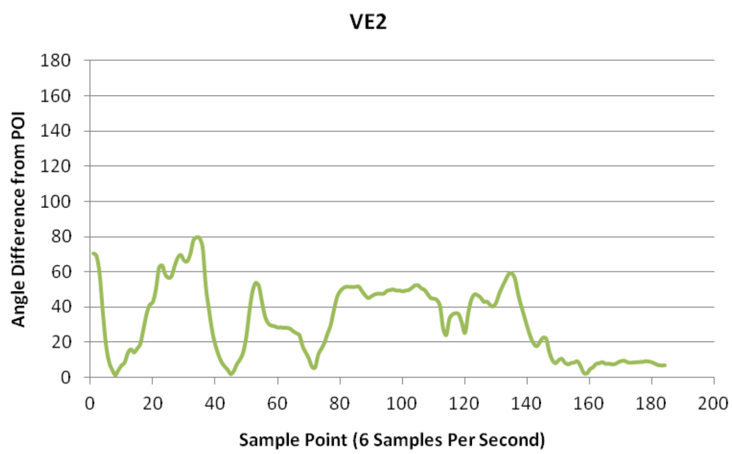


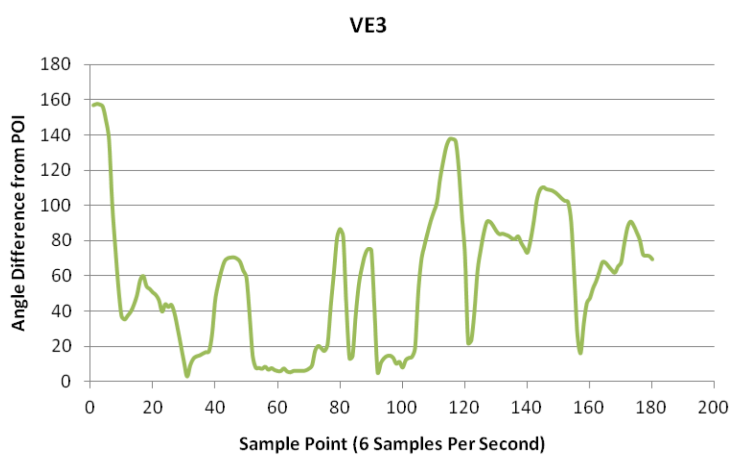




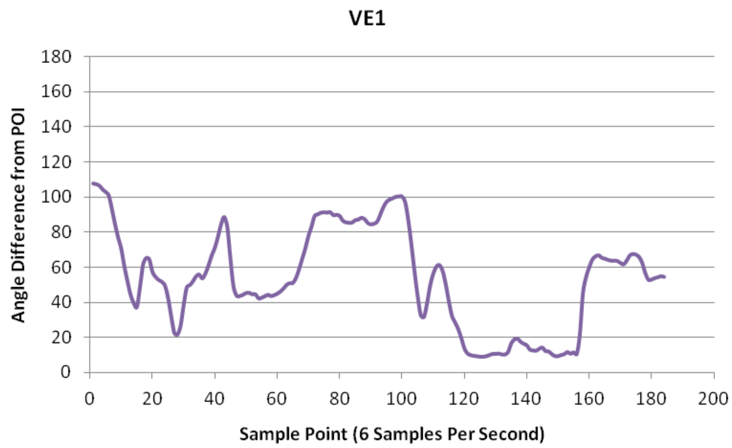
Participant 2017-10-10_03 Group: Reduced Stimulus

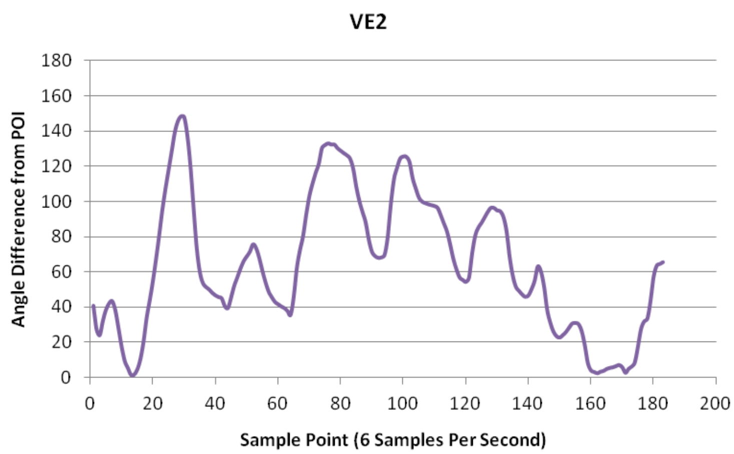


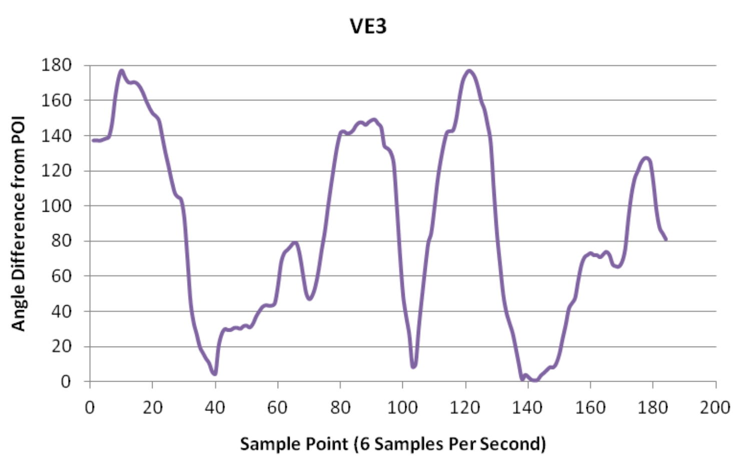




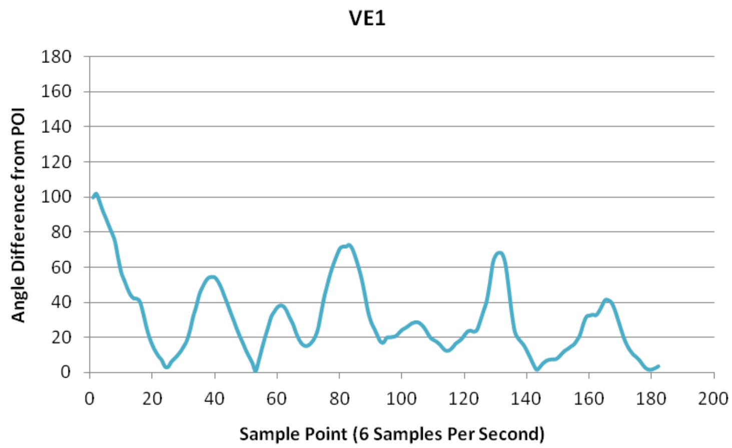
Participant 2017-10-10_04 Group: Reduced Stimulus

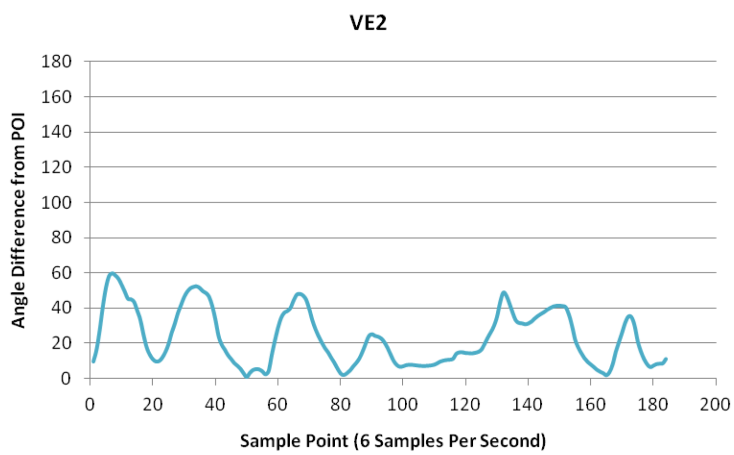


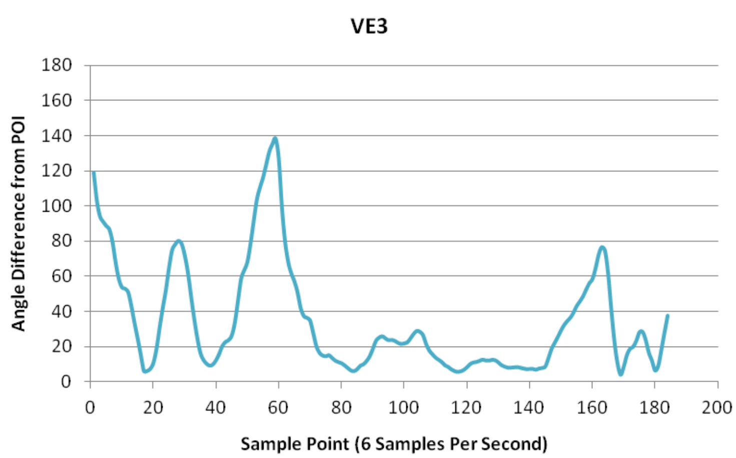




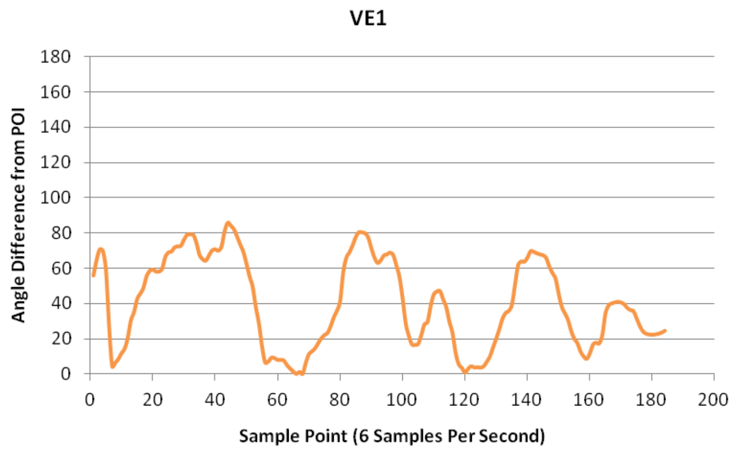
Participant 2017-10-10_05 Group: Reduced Stimulus

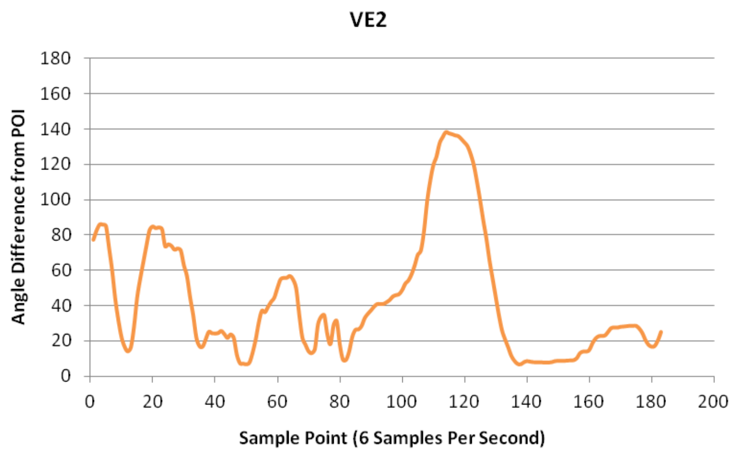


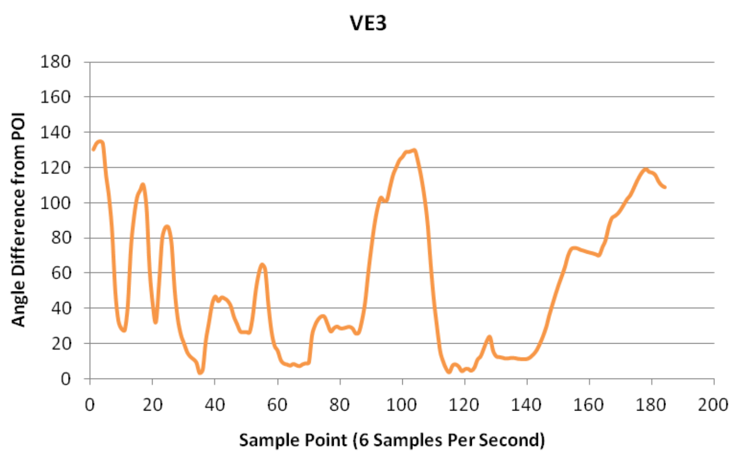




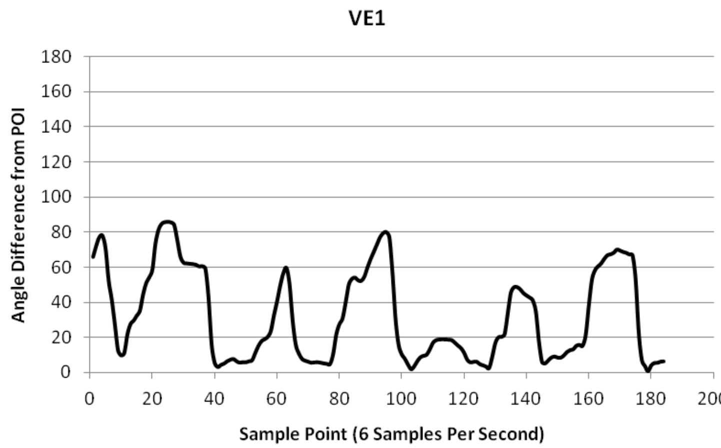
Participant 2017-10-10_06 Group: Reduced Stimulus

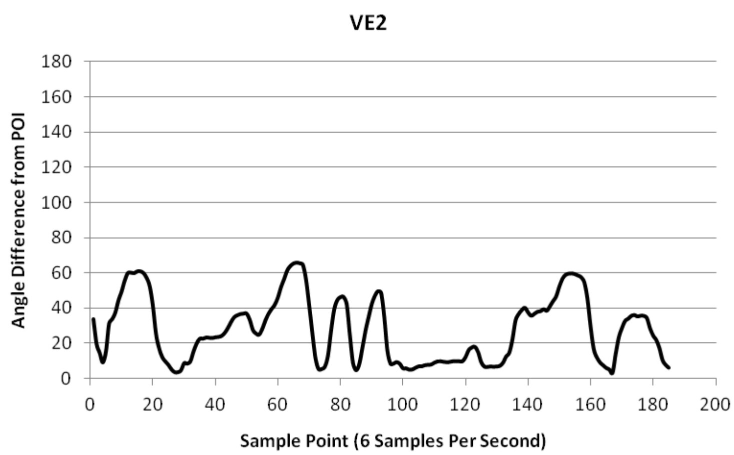


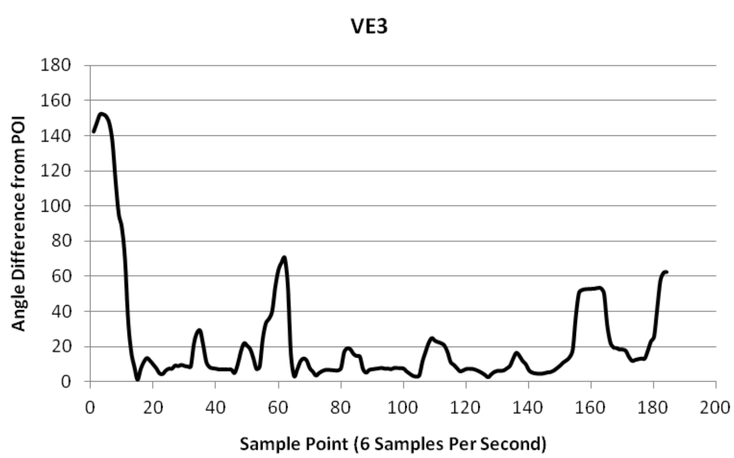




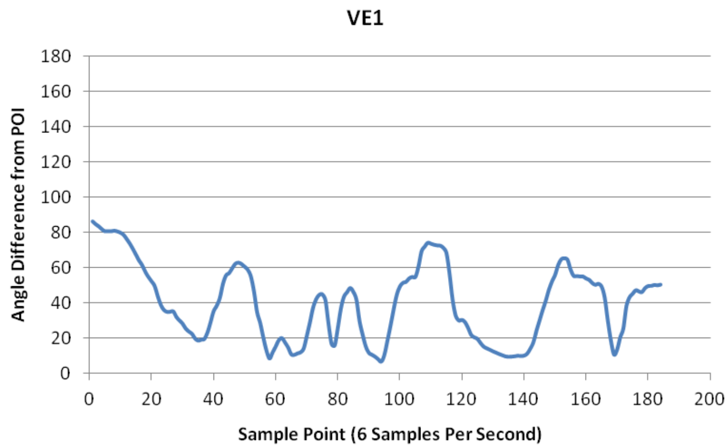
Participant 2017-10-16_03 Group: Reduced Stimulus

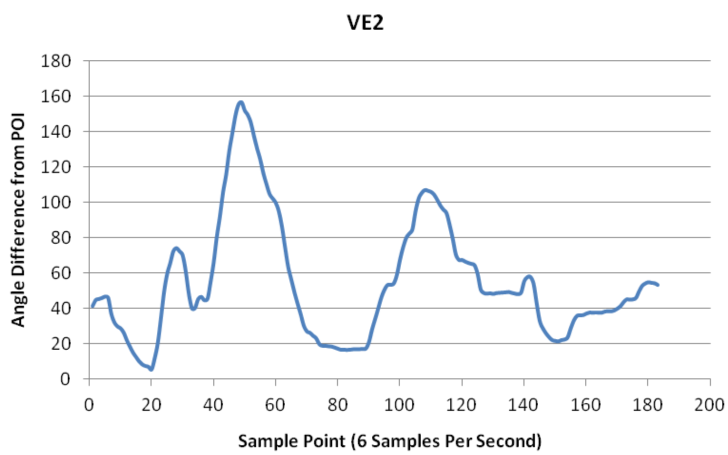


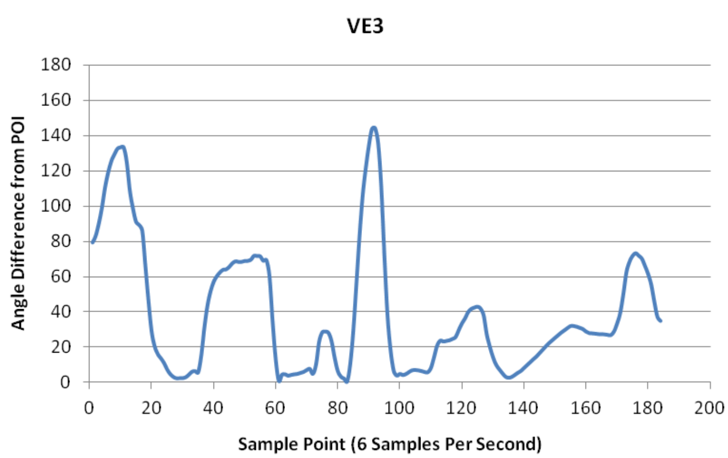




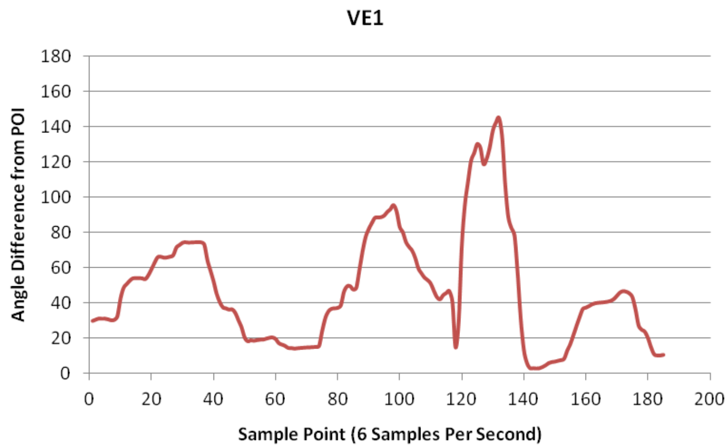
Participant 2017-11-08_03 Group: Reduced Stimulus

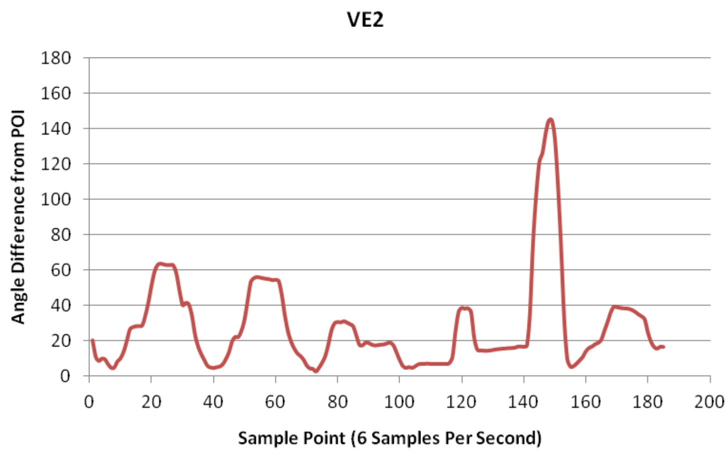


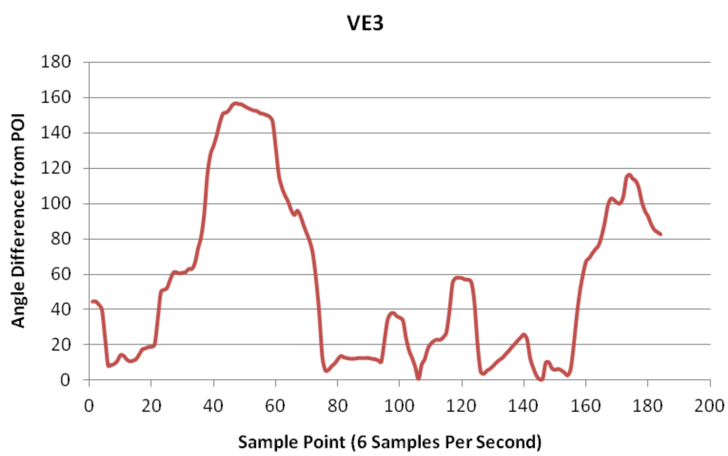




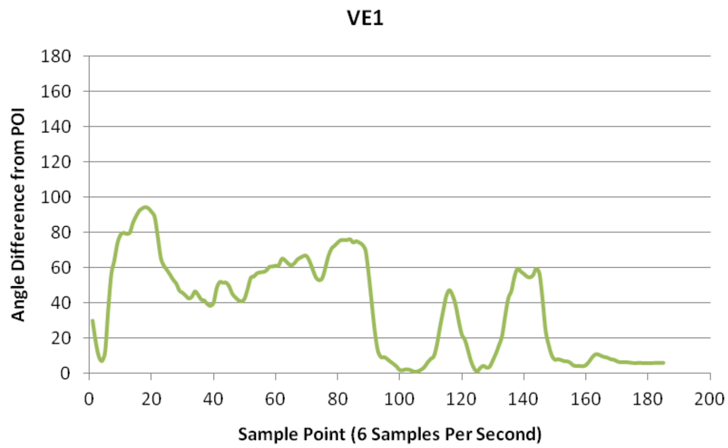
Participant 2017-11-29_01 Group: Reduced Stimulus

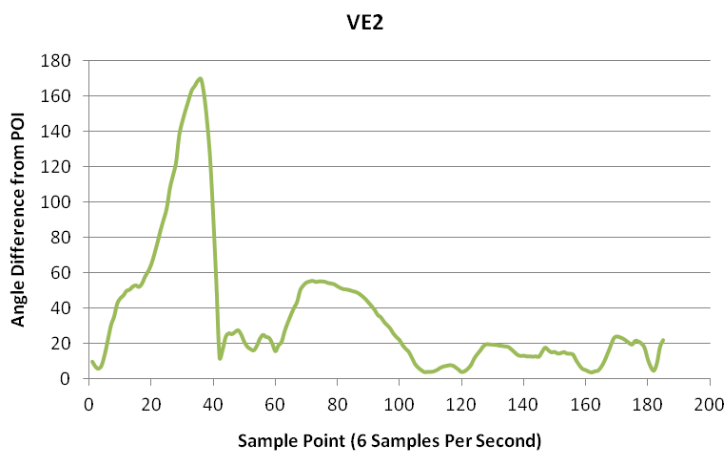


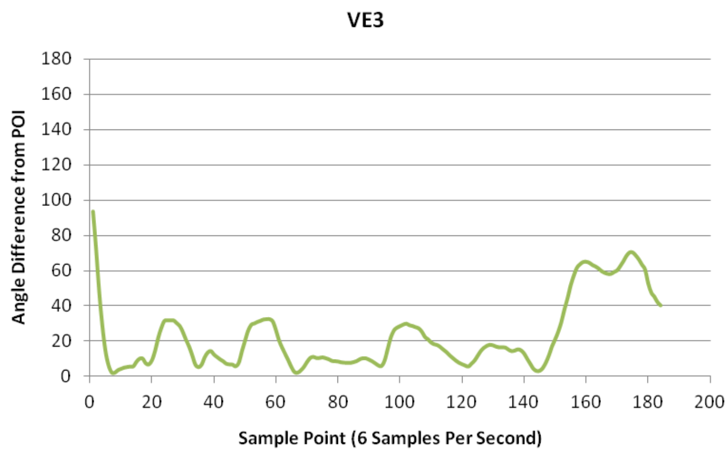




Participant 2017-11-29_02 Group: Reduced Stimulus






VE3
180
160
140
120
100
80
60
40
20
0
Angle Difference from POI
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20
40
60
80
100
120
140
160
180
200
Sample Point (6 Samples Per Second)