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Similarity Measures of Object Selection in Interactive Applications based on Smooth Pursuit Eye Movements

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***Abstract*—Gaze-based interaction in various digital technologies is a rapidly growing research area. Eye tracking provides an alternative input modality to control interactive contents in computers. Nowadays, eye tracking is not only expected to be a personal assistive technology, but also to be a controller for interactive contents in a public display. Instead of fixational eye movement, smooth pursuit eye movement has been used for object selection in gaze-based interactive applications. However, previous works did not consider various similarity measures for spontaneous object selection. Hence, no information on how different similarity measures affect performance of object selection. To fill this gap, we compared two similarity measures—Euclidean distance and Pearson's product moment coefficient—for object selection. We presented simple interactive applications containing four dynamic objects, each of which was presented subsequently or simultaneously. The participants were asked to select the objects by gazing and following the trajectory of the moving objects. Our results show that object selection with Euclidean distance achieved superior accuracy (78.65%) compared with object selection with Pearson's product moment coefficient (57.38%). In future, our results maybe used as a guideline for development of spontaneous gaze-based interactive application.**

***Index Terms*—smooth pursuit, eye tracking, Euclidean distance, Pearson's product coefficient, gaze-based interaction**

I. INTRODUCTION

Gaze-based interaction in digital technologies is an important research area because it provides a faster and effortless input modality to interact with multimedia contents. Eye tracking is expected to do various actions normally performed by mouse and keyboard, such as object selection, navigating, and modification across various multimedia contents [1]–[5].

Gaze-based interfaces typically implement one out of three eye movements to control the contents: fixation, saccade, and smooth pursuit eye movement [6]. Fixation is the most common eye movement used in gaze-based interactive applications [7]–[10]. Fixation is detected during stationary gaze, in which the eye observes a particular object of interest with 200-300 ms of duration. Saccade represents a change of attention from one point to other point with 30-80 ms of duration. Saccadic eye movement has been used as a gaze-based control for video games that require quick navigation [11], [12]. Finally, smooth pursuit is a condition during which the eye follows a dynamic object with velocity about $10° - 30°/s$. In recent studies, smooth pursuit was implemented in various interactive applications [13]–[18].

On the other side, the usage of eye tracking has expanded from personal assistive technology to interactive applications in public display [19]–[21]. Zhang et al. [19] proposed a method to identify gaze position for spontaneous interaction in public display. This work was subsequently followed by a proposal of interactive assistance during interaction in public display [20]. Additionally, Khamis et al. [21] also proposed an interactive application in public display by giving some options to the users for error correction activities.

Although interaction in public display has been studied extensively, simple calibration procedure remains to be the main challenge of this research area. Unfortunately, many commercial eye trackers still implement fixation-based calibration to obtain precise spatial gaze point [6]. In case the result of calibration is poor, the user must repeat the calibration procedure—impractical for on-the-go interaction in a public display. In this case, smooth pursuit eye movement has been used as a controller during interaction by finding the best similarity between trajectory of the eye movements and trajectory of the moving stimulus [14]–[18]. However, previous works did not investigate effect of different similarity measures on performance of object selection in interactive applications.

To fill this research gap, we compared performance of two similarity measures—Euclidean distance and Pearson's moment coefficient—for object selection with smooth pursuit eye movement in interactive applications. We observed accuracy and success timing of selecting dynamic objects with various movement directions. We also investigated the effect of chinrest on accuracy and success timing of object selection. Results of this study is useful for development of more accurate spontaneous gaze-based interaction.

II. MATERIALS AND METHODS

A. Apparatus

In this study, we used a personal notebook Acer Aspire E5-475G with Intel Core i5 2.5GHz, 4GB RAM DDR4, and 22 inch screen HD LED display. The Tobii EyeX Controller eye

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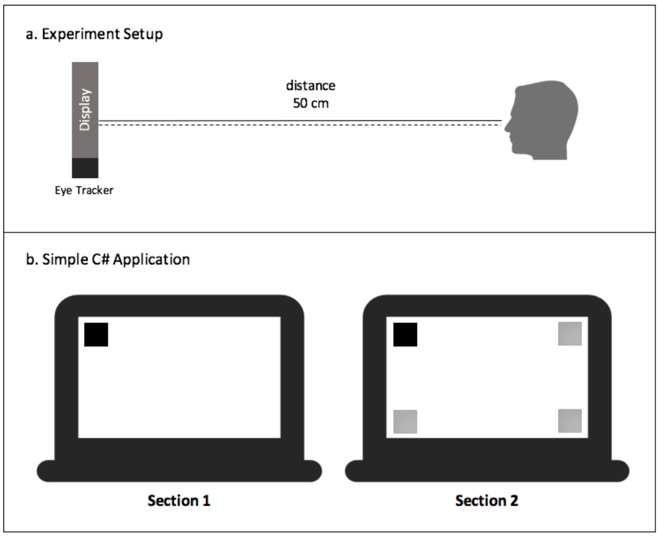

Fig. 1. Experimental setting: (a) The participant was positioned about 50 cm from the display. The eye tracker was installed beneath the display; (b) Simple C# applications presented stimulus for the experiment. There were two sections, each of which presenting objects subsequently or simultaneously. The objects were positioned at the corner of the display. Section 1 presented dynamic objects subsequently and section 2 presented four dynamic objects simultaneously. The participant was asked to follow the black object as an active object.

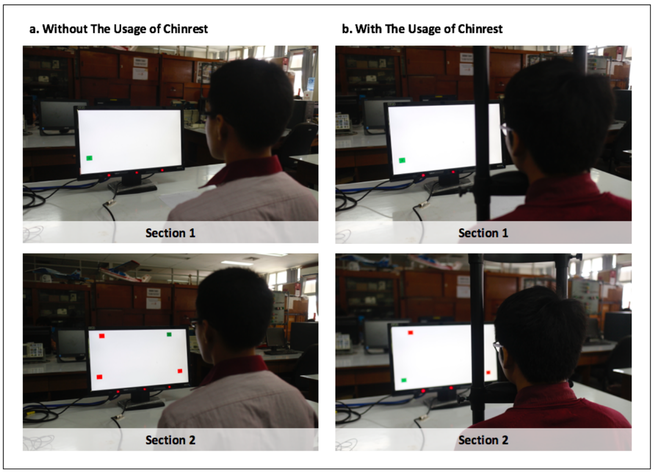

Fig. 2. Experimental setting: (a) Left panel shows section 1 and 2 without the usage of chinrest; (b) Right panel shows section 1 and 2 with the usage of chinrest.

tracker was used as a sensor of interactive applications. The eye tracker was installed beneath the display. The participants sit 50 cm in front of the display. The eye tracker was used to collect eye movements data with 70 Hz of sampling rate. A custom-built chinrest was used to gently hold participant's head. Figs. 1 and 2 present experimental setting in this study.

B. Participants

Twenty three participants ($N = 23$) were recruited on voluntary basis (M=12; F=11). Their ages ranged from 21 to 40 years (mean = 25.41 years, S.D.= 4.05 years). The average height of the participants was 163.59 cm (S.D.= 9.71 cm). All participants were healthy, with normal or corrected eyes.

C. Procedures of experiment

Authors confirmed that all experiment procedures were arranged according to WMA Declaration of Helsinki (*Ethical Principles for Medical Research Involving Human Subjects*). Before the experiment began, all participants were asked to read and to sign an informed consent explaining experiment procedures. Next, the participants were asked to fill in demographic data, such as gender, age, height, and usage of prescriptive glasses. A trial section was provided for each participant to provide a brief overview and a short practice of the experiment.

Figure 1 shows experimental setting. The experiment was divided into two sections. In the first section, the participants were asked to follow a dynamic object that appeared subsequently at different positions on the display: (i) top left, (ii) bottom left, (iii) top right, (iv) bottom right. The size of the dynamic object was 77 x 66 pixels of width and height, respectively. The object moved on 79 pixels of trajectory with 26.33 pixels/second of velocity. The horizontal and vertical distance between the top left pixel of the object and the border of the screen were 30 pixels. The object moved back and forth in horizontal direction while appearing at the top position. Conversely, the object moved back and forth in vertical direction while appearing at the bottom part of the display.

In the second section, four dynamic objects appeared simultaneously at the designated positions. The positions were similar as in the first session. The active object was set to be green color while the inactive objects were set to be red color. The participant was asked to follow the active object. The sequence of activation was: (i) top left, (ii) bottom left, (iii) top right, (iv) bottom right. The experiment was conducted with and without the usage of chinrest. Fig. 2 shows a participant performed the experiment without (left panel) and with chinrest (right panel). More information about the experimental setting can be found in `http://ugm.id/gazepursuit`.

D. Methods of object selection

Object selection using smooth pursuit can be done by identifying a visual stimuli that has the most similar trajectory with the trajectory of eye movement in a particular time frame. In this research, two similarity measures were examined: Euclidean distance (ED) and Pearson's product moment coefficient (PPMC). The ED method is based on absolute distance between the position of the gaze point and the position of the stimuli. On the other side, the PPMC method is based on correlation of spatial position between the gaze point and the stimuli. Given more than one moving objects in an interactive application, the selected object should have the shortest gaze-to-object distance or the largest correlation value between the gaze point coordinates and the stimuli coordinates.

1) Euclidean distance (ED): A sequence G of observed gaze points $g = (g_x, g_y)_t$ during a time span t can be defined as:

$$G = [g_0, ..., g_t] \quad (1)$$

Let L be a set of observation sequences L^o for N objects, by which $o = 1, ..., N$. The location of the object o at time step t is denoted by $l_t^o = \{l_x^o, l_y^o\}$. L and L^o can be defined as follows:

$$L = [L_0, ..., L_n] \quad (2)$$

$$L^o = [L_0^o, ..., L_t^o] \quad (3)$$

To select an object o that was gazed by the participant during a time span $t\epsilon[i, k]$, a distance $D^o(G, L^o)$ between the observed gaze points G and the observed locations of the object L^o was computed:

$$D^o(G, L^o) = \sum_{t=i}^{k} \|g_t - l_t^o\| \quad (4)$$

Hence,

$$D^o(G, L^o) = \sum_{t=i}^{k} \sqrt{(g_{xt} - l_{xt}^o)^2 + (g_{yt} - l_{yt}^o)^2} \quad (5)$$

If the computed $D^o(G, L^o)$ was smaller than a threshold $D_H^o(G, L^o)$, than the object o was selected. We empirically set $C_H^o(G, L^o) = 100$ pixels.

2) Pearson's product correlation moment (PPMC): PPMC has different perspective compared with ED. ED focuses on absolute distance between the observed gaze points G and the observed locations of the object L^o. However, PPMC focuses on the similarity of movement pattern between the observed gaze points G and the observed locations of the object L^o. If the object moves in X axis, we used the X coordinates for N last historical coordinates to compute the correlation value. Similar approach was used for Y coordinates.

Hence,

$$C^o(G, L^o) = \frac{N(\sum GL^o) - (\sum G)(\sum L^o)}{\sqrt{[N(\sum G^2) - (\sum G)^2][N(\sum L^{o2}) - (\sum L^o)^2]}} \quad (6)$$

If the computed $C^o(G, L^o)$ was greater than a threshold $C_H^o(G, L^o)$, than the object o was selected. We empirically set $C_H^o(G, L^o) = 0.2$.

III. EXPERIMENTAL RESULTS

A. Effect of Chinrest Usage and Similarity Measures on Accuracy and Success Timing of Object Selection

In the first section of experimental results, we compared effects of chinrest usage and similarity measures on accuracy and success timing of object selection. Object selection accuracy is presented as the percentage of an amount of

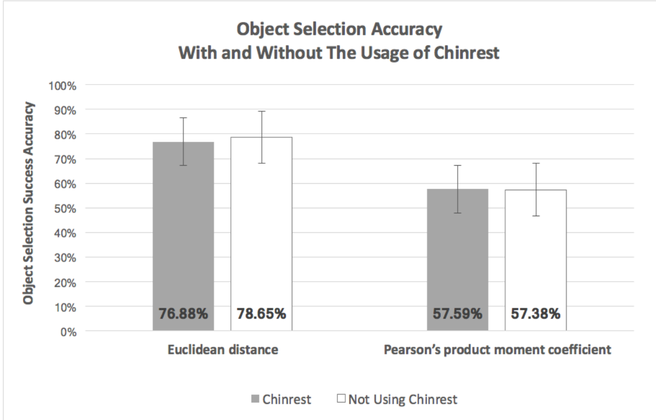

Fig. 3. The accuracy of object selection with Euclidean distance and Pearson's product moment coefficient during experiment with and without the usage of chinrest.

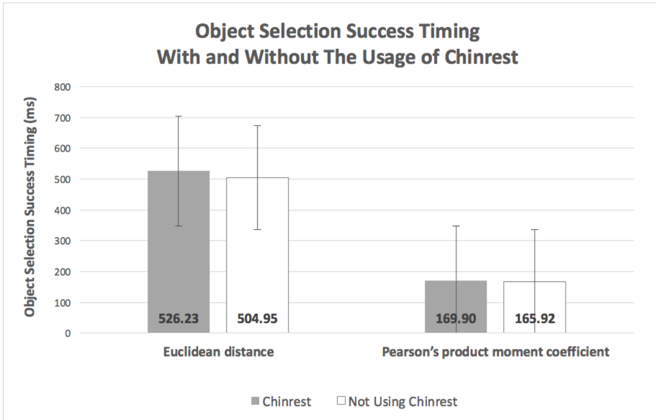

Fig. 4. The success timing of object selection with Euclidean distance and Pearson's product moment coefficient during experiment with and without the usage of chinrest.

successful object selection task in all sections of experiment. Object selection success timing is shown as time spent by the participant to successfully select an object of interest in all sections of experiment. We did not implement any signal processing filter on the eye tracking data.

Figure 3 shows the accuracy of object selection for different usage of chinrest—with vs. without—and different similarity measures—Euclidean distance (ED) vs. Pearson's product moment coefficient (PPMC). With the usage of chinrest, the average accuracy of object selection with ED and PPMC were 76.88±14.54% and 57.59±3.29%, respectively. On the other hand, object selection with ED shows better accuracy (78.65±11.95%) than object selection with PPMC (57.38±3.51%) when the participants did not use chinrest.

Figure 4 shows the success timing of object selection for different usage of chinrest—with vs. without—and different similarity measures—Euclidean distance (ED) vs. Pearson's product moment coefficient (PPMC). With the usage of chinrest, the average success timing of object selection using ED and PPMC were 526.23±83.01 ms and 169.90±59.57

$$\underset{(A)}{\begin{bmatrix} 1 & 0 & 0.2 & 0 \\ 0 & 1 & 0 & 0.2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}} \underset{(B)}{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}} \underset{(H)}{\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}}$$

$$\underset{(Q)}{\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0 \\ 0 & 0 & 0 & 0.1 \end{bmatrix}} \underset{(R)}{\begin{bmatrix} 0.1 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 \\ 0 & 0 & 0.1 & 0 \\ 0 & 0 & 0 & 0.1 \end{bmatrix}}$$

Fig. 5. Covariance matrix as parameter setting for Kalman filter. (A) is state transition matrix, (B) is input control matrix, (H) is measurement matrix, (Q) is action uncertainty matrix, and (R) is sensor noise matrix.

ms, respectively. Without the usage of chinrest, the average success timing of object selection with ED and PPMC were 504.95±68.64 ms and 165.92±8.04 ms, respectively.

Two way within-subjects analysis of variance (ANOVA) was performed on the experimental results. The independent variables were chinrest usage (with vs. without) and similarity measures (ED vs. PPMC). The dependent variables were accuracy and success timing of object selection. We found significant effects of similarity measures on accuracy ($F(1, 22) = 100.29, p < 0.001$) and success timing of object selection ($F(1, 22) = 636.98, p < 0.001$). We did not find significant effect of chinrest usage and interaction of chinrest usage × similarity measures on accuracy and success timing of object selection.

B. Effect of Signal Processing Filters and Similarity Measures on Accuracy and Success Timing of Object Selection

In the second section of experimental results, we implemented three signal processing filters on the eye tracking data: Moving average filter, Kalman filter, and Particle filter. We used five latest eye gaze data as input of the Moving average filter. Additionally, we used 100 particles as input for the Particle filter to calculate setting of parameters. For the Kalman filter, we used covariance matrices shown in Fig. 5. We observed the effects of signal processing filters and similarity measures on accuracy and success timing of object selection. From demographic data, 19 out of 23 participants (82.61%) stated that chinrest is not comfortable. Thus they opted not to use the chinrest whenever it is possible. Our previous analysis shows that there is no significant difference in accuracy and success timing of object selection performed with and without chinrest usage. Hence, all data in this section were taken from object selection task without chinrest usage.

Figure 6 and 7 show accuracy and success timing of object selection with Euclidean distance (ED) and Pearson's product moment coefficient (PPMC) under four filtering conditions: (i) raw (no filtering), (ii) Moving average filter, (iii) Kalman filter, (iv) Particle filter. We found that incorporating Kalman

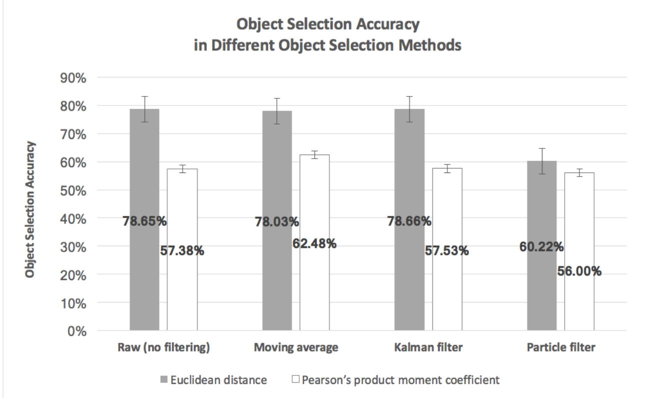

Fig. 6. The accuracy of object selection with Euclidean distance and Pearson's product moment coefficient under four filtering conditions.

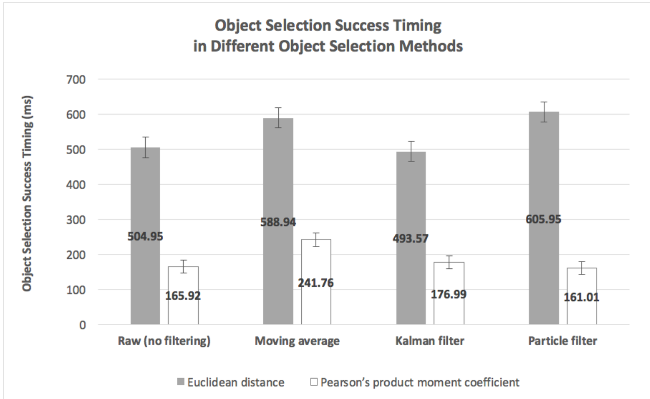

Fig. 7. The success timing of object selection with Euclidean distance and Pearson's product moment coefficient under four filtering conditions.

filter in object selection with ED yielded highest accuracy (78.66±11.68%). On the contrary, success timing of object selection was achieved faster when Particle filter was incorporated with PPMC (161.01±48.05 ms).

Two way within-subjects analysis of variance (ANOVA) was performed on the experimental results. The independent variables were filtering conditions (no filter vs. Kalman filter vs. Moving average filter vs. Particle filter) and similarity measures (ED vs. PPMC). The dependent variables were accuracy and success timing of object selection. We found significant effects of filtering conditions ($F(3, 66) = 11.61, p < 0.001$), similarity measures ($F(1, 22) = 94.81, p < 0.001$), and interaction of filtering conditions × similarity measures ($F(3, 66) = 6.28, p < 0.001$) on accuracy of object selection. Furthermore, we also observed significant effects of filtering conditions ($F(3, 66) = 7.42, p < 0.001$), similarity measures ($F(1, 22) = 632.35, p < 0.001$), and interaction of filtering conditions × similarity measures ($F(3, 66) = 3.90, p < 0.01$) on success timing of object selection.

IV. DISCUSSION

In the first section of experimental results, we show that there was no significant effect of chinrest omission on accuracy and success timing of object selection. Indeed, the usage of chinrest limits head movements [22]. Compared with fixation-based eye tracking calibration, we argue that object selection using smooth pursuit eye movement can be implemented without restricting head movements. In this case, we also observed that Euclidean distance was more suitable for object selection as it achieved higher accuracy than Pearson's product moment coefficient ($p < 0.001$).

Euclidean distance was more superior in accuracy than Pearson's product moment coefficient ($p < 0.001$). Object selection with Euclidean distance achieved higher accuracy (21.27%) than Pearson's product moment coefficient. Euclidean distance measured the object selection based on absolute distance of the gaze point and the stimuli. Euclidean distance performed best when the object was positioned in a wide range.

On the contrary, Pearson's product moment coefficient estimated pattern similarity between trajectory of the gaze point and the stimuli. There was ambiguity on pattern similarity as there were more than one object moving in similar direction. This ambiguity led to decrement of accuracy of the Pearson's product moment coefficient. Based on our experimental results, we argue that accuracy of object selection based on smooth pursuit eye movement can be achieved by considering absolute distance of the gaze point and the stimuli while ignoring similarity of trajectory between the gaze point and the object.

On the other hand, we found that Pearson's product moment coefficient was more superior in success timing than Euclidean distance ($p < 0.001$). Object selection with Pearson's product moment coefficient was 67% faster compared with its counterpart. On the other hand, Card et al. [23] has shown that applied psychology can be used to estimate the duration between a stimuli presented on the monitor and a response of user on the stimuli. During this short decision making, Card et al. stated that average reaction time of a user towards a stimuli is about 310 ms, with 130 and 640 ms for the fastest and slowest response, respectively. In this study, we found that object selection task with Euclidean distance required in average 526.23 ms (with chinrest, no filtering) and 605.95 ms (without chinrest, Particle filter). Therefore, we argue that object selection with Euclidean distance is still reasonable for wider interactive applications as it requires less than 640 ms to respond the presented stimuli.

The usage of signal processing filters enhanced the accuracy of object selection using smooth pursuit eye movement. We observed that object selection with Kalman filter achieved slightly higher accuracy (78.66%) than object selection with Moving average filter (78.03%). Object selection with Particle filter has the lowest accuracy, because Particle filter need at least two sources for the calculation to performs the best in accuracy. However, in this study, we used only one source (from eye tracker) and 100 particles for eye gaze filtering purpose. On the other hand, object selection with Kalman filter spent fewer time (493.57 ms) than object selection with Moving average (588.94 ms) and Particle filter (605.95 ms). In fact, the low computational complexity of Kalman filter can be associated with the scarcity of the model matrix. Therefore, the algorithm simplifies matrix multiplications and inversion. In future, Kalman filter maybe used in various real-time interactive applications due to its low computational overhead.

V. CONCLUSION

Smooth pursuit eye movement has been used as an alternative controller for on-the-go interaction on public display. Similarity measures are normally used to find the best match of eye movement's and stimulus' trajectory. However, previous works did not investigate effect of different similarity measures towards performance of object selection in gaze-based applications. In this research, we investigate the effect of chinrest usage (i.e. with and without chinrest) and different similarity measures (i.e. Euclidean distance and Pearson's product moment coefficient) towards accuracy and success timing of object selection. From our experimental results, we did not find any significant effect of chinrest usage on accuracy and success timing of object selection. Our results show that object selection with Euclidean distance achieved superior accuracy (78.65%) compared with object selection with Pearson's product moment coefficient (57.38%). Although Pearson's product moment coefficient was faster in success timing, implementing Euclidean distance was still reasonable as its average success timing (605.95 ms, without chinrest) was under the recommended estimation of normal cognitive response (640 ms). In future, our results can be used as a guideline for development of spontaneous gaze-based interactive application.

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