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Behavioral Analysis of Smooth Pursuit Eye Movements for Interaction

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Gaze has been found challenging to use in dynamic interfaces involving motion. Moving targets are hard to select with state of the art gaze input methods and gaze estimation requires calibration in order to be accurate when offering a successful experience. Smooth Pursuit eye movements broaden opportunities to extend novel interfaces and promise new ways of interaction. However, there is not enough information on the natural behavior of the eyes when performing them. In this work, we tried to understand the relationship between Smooth Pursuits and motion, focusing on movement speed and direction. Results show anticipatory movements when performing pursuits, indicating that the natural behavior of the eyes to predict the displayed movement. Results could help in the design of interfaces and algorithms that use Smooth Pursuit for interaction.

Keywords: Eye movement; Gaze; Eye tracking; Smooth Pursuit; Gaze interaction

Introduction

Smooth Pursuit eye movements have become a compelling tool for gaze interaction. Leveraging the natural attention of the eyes when motion is presented (Kang & Malpeli, 2003), pursuits helped developing new interfaces able to use gaze for selection without the need of calibration (Vidal, Bulling, & Gellersen, 2013). Other examples include widget control (Špakov, Isokoski, Kangas, Akkil, & Majaranta, 2016) for desktop applications, or smart watches (Esteves, Velloso, Bulling, & Gellersen, 2015), allowing hands-free interaction in small devices. Further research proposed pursuits as a new method for implicit calibration (Pfeuffer, Vidal, Turner, Bulling, & Gellersen, 2013), less tedious than standardized methods, robust and with potential to be embedded within the application context.

However, gaze interaction using Smooth Pursuit movements has been designed regardless calibration, hence no knowledge about precision or what is the concrete behavior when performed.

Method

In order to understand how Smooth Pursuit movements interact with presented motion we asked participants during a user study to follow with their gaze a dot (circle) performing different movements. We designed the target's motion as closed paths containing horizontal, vertical, diagonal or circular directions, plus random built with 4 Bezier curves. We used 6 different constant speeds, measured in ° (degrees) of visual angle per second, (1.5°/s, 6°/s, 12°/s, 18°/s, 24°/s and 30°/s) to test the boundaries between performing eye fixations or saccadic movements (Holmqvist et al., 2011). Both target and gaze position were recorded using a Tobii Pro TX300 eye tracker integrated under a 23” monitor.

12 volunteer participants, between 20 and 40 years ($M = 27$, $SD = 5$, 6 female, 4 wearing glasses), performed the user study. During the study, participants followed the moving dot displayed on the screen with their gaze during 2 rounds consisting of 36 randomized trials trying to move the least possible. Further, a 3 seconds interval between trials was used as a break to rest the eyes. Before each round, the eye tracker was calibrated to avoid a drop in the quality of estimated gaze data between rounds. A gaze accuracy test was performed before and after each of them to assure that the accuracy was maintained during the round.

Results

We aimed to maintain the estimated gaze accuracy level between rounds to assure gaze data was not compromised during the study. Results from both accuracy tests performed before ($M = 1.21°$, $SD = 0.34°$) and after ($M = 1.23°$, $SD = 0.33°$) each round showed how gaze accuracy is maintained during the experiment, reporting $M = 1.22°$, $SD = 0.33°$.

Recorded gaze data during the study was analyzed to detect Smooth Pursuit eye movements (Pfeuffer et al., 2013; Vidal et al., 2013), using points with a *Pearson's correlation coefficient* higher than 0.7 and a 30 samples moving window. *Figure 1* show the effect Direction and Speed have when sort-

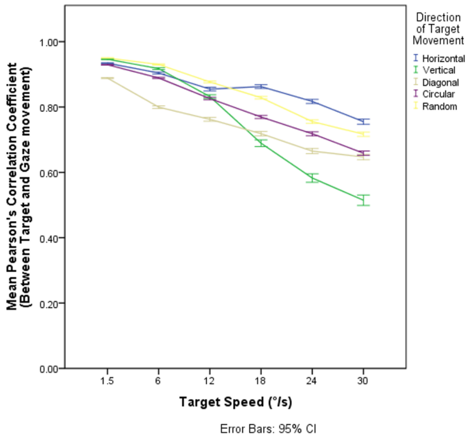

Figure 1. *Pearson's correlation coefficient* evolution depending on speed per each different direction of movement.

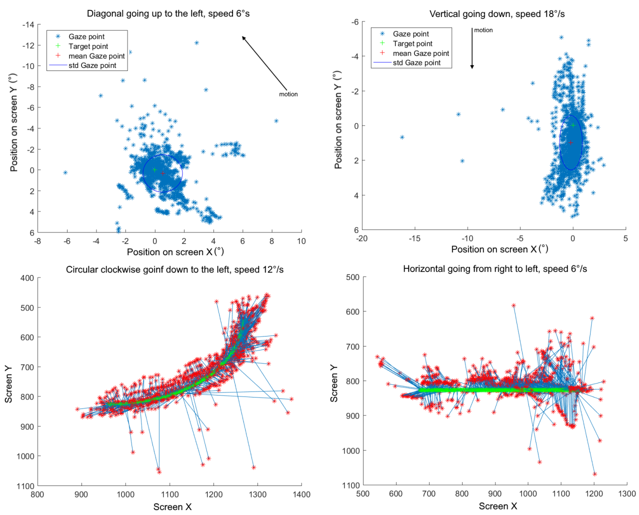

Figure 2. Gaze position versus target trajectory scatter plots showing gaze behavior. (Top, left) Gaze is delayed. (Top, right) Gaze is ahead. (Bottom) Points during movements.

ing gaze movements as Smooth Pursuits (according to correlation coefficient). For slow speeds (1.5, 6 and 12 °/s) correlation coefficient scored higher mean values than for faster speeds (18, 24 and 30 °/s), showing that Smooth Pursuit eye movements are harder to perform in high speed conditions.

A two-way repeated measures ANOVA showed a statistically significant difference in gaze correlation for the main effect of direction ($F(2.199, 24.187) = 132.734$, $p<.001$) and the effect of speed ($F(5, 55) = 336.633$, $p<.0005$), and both ($F(20, 220) = 45.633$, $p<.0005$). Simple main effects were run. Correlation coefficient results were not statistically significantly different for Horizontal movement (0.91 ± 0.15) compared to Random one (0.92 ± 0.15), with $p = .098$. There was no difference between Vertical (0.89 ± 0.19) and Diagonal (0.84 ± 0.23) movements, with $p = 1$. Circular movement was significantly different to the rest of directions, with $p <.001$. Vertical, Circular and Random movements showed to be dependent to speed, whereas Horizontal and Diagonal showed less difference between consequent speeds. We did not find any statistically significant interaction between directions and speed on gaze and target points distance.

We analyzed the mean distance between estimated gaze and the target points. We observed how it increases with the increment of speed, decreasing its accuracy. Directions involving descending motion reported gaze being ahead from the target. Horizontal (left to right) movement also showed the same anticipation. Movements involving ascending motion and horizontal to the left reported gaze to be delayed from the target for slow speeds (1.5°/s, 6°/s and 12°/s), whereas for the fast ones gaze shows to be onwards. *Figure 2* represents both behaviors.

Discussion

Research in Human-Computer interaction using Smooth Pursuit eye movements considers that when motion is presented, gaze cannot help but follow that movement. While this could imply a delayed gaze trajectory when following the target's motion, our approach to understand the characteristics of eye movement showed a more complex behavior.

Results show how our ability to follow movement is dependent on the speed of the target, affecting the detection of Smooth Pursuit eye movements. *Figure 1* indicates that in order to be able to successfully and accurately detect pursuits, target' speed should be between 1.5°/s and 24°/s. Moreover, we found that vertical movements should be avoided for Smooth Pursuit interaction. They scored lower detection values, as it is not a common eye movement in everyday activities (Collewijn & Tamminga, 1984).

Further results suggest that gaze starts following the movement (delayed), but changes behavior tending to predict the forthcoming target motion. Movements left to right and descending directions reported gaze position to be ahead of target trajectory (*Figure 2*). This is related to the natural phase shift of Smooth Pursuit lag during its movement (Holmqvist et al., 2011). This behavior needs to be considered to improve Smooth Pursuit detection for novel interfaces including this calibration free gaze interaction.

Conclusion

Our study helped to gain a better understanding of Smooth Pursuit eye movements behavior when motion on-screen is presented. Our user study results indicate that there is an anticipation of the movements pointing towards a predictive behavior of the eyes when motion is presented. Moreover, we propose guidelines of which movement features should be used when designing new interfaces that leverage Smooth Pursuit eye movements for hands-free interaction.

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