Hidden Pursuits: Evaluating Gaze-selection via Pursuits when the Stimuli's Trajectory is Partially Hidden

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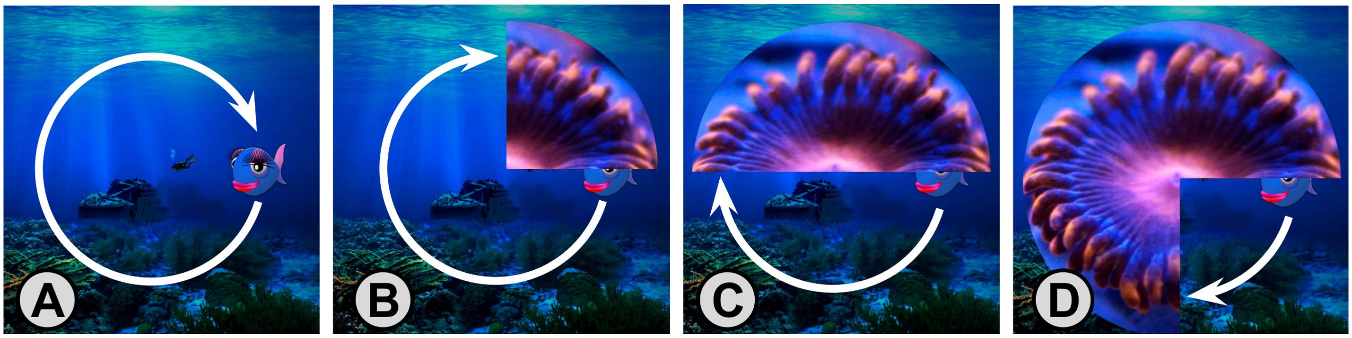

Figure 1: We explore HiddenPursuits, where the trajectory of a moving target is partially hidden while users perform selections via smooth pursuit eye movements. This allows (1) expanding selection areas by enabling targets to move out of the bounds of small displays (e.g., mobile devices and smartwatches), and (2) selection of targets even if they are partially occluded (e.g., in VR). In our user study, we hid 0%, 25%, 50% and 75% of the target's (fish) trajectories, and measured how well eye movements correlate with the anticipated target's trajectory. Arrows are for illustration and were not displayed.

ABSTRACT

The idea behind gaze interaction using Pursuits is to leverage the human's smooth pursuit eye movements performed when following moving targets. However, humans can also anticipate where a moving target would reappear if it temporarily hides from their view. In this work, we investigate how well users can select targets using Pursuits in cases where the target's trajectory is partially invisible (HiddenPursuits): e.g., can users select a moving target that temporarily hides behind another object? Although HiddenPursuits was not studied in the context of interaction before, understanding how well users can perform HiddenPursuits presents numerous opportunities, particularly for small interfaces where a target's trajectory can cover area outside of the screen. We found that users can still select targets quickly via Pursuits even if their trajectory is up to 50% hidden, and at the expense of longer selection times when the hidden portion is larger. We discuss how gaze-based interfaces can leverage HiddenPursuits for an improved user experience.

CCS CONCEPTS

• **Human-centered computing** → **Interaction paradigms**; **Interaction techniques**;

KEYWORDS

Smooth Pursuit, Hidden trajectory, Displays, Motion Correlation

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1 INTRODUCTION

Gaze-based interaction using smooth pursuit eye movements, aka Pursuits [Vidal et al. 2013], has been gaining popularity in the past years. Rather than determining a precise gaze point, the idea is to allow the user to select targets by having the targets move in distinct trajectories, and then comparing the eye movements to that of the moving targets; the target whose trajectory correlated the most with that of the eye is deemed the one being gazed at.

However, a problem is that in some use case, the target might not always be visible to the user throughout its trajectory. For example, if the screen size is small (e.g., Pursuits on smartwatches [Esteves et al. 2015]), the moving target might temporarily move out of the bounds of the screen. Another example is use cases where the target might temporarily move behind another object (e.g., Pursuits in VR [Khamis et al. 2018]). We refer to cases where the pursued target is temporarily hidden as "HiddenPursuits". To date, it is not clear how well Pursuits performs when the target is temporarily hidden. HiddenPursuits was never studied before in HCI context, therefore investigating HiddenPursuits would not only allow understanding selection of targets whose trajectories are partially hidden, but also inform the design of Pursuits applications on small displays by expanding selection options beyond the screen's bounds.

In this work, we explore HiddenPursuits through a user study (N=17), in which we systematically hid parts of a target's trajectory as users followed it with their eyes. We found that the larger the hidden portion of the trajectory the lower the selection accuracy, nevertheless users can still perform quick HiddenPursuits selections even when 50% of a circular trajectory is hidden (see Figure 1C).

The core contribution of this paper is a systematic evaluation and understanding of HiddenPursuits.

2 RELATED WORK

Our work builds on previous work in interaction using smooth pursuit eye movements. Gaze-based interaction using said movements is referred to as "Pursuits" [Vidal et al. 2013]. The technique relies on comparing the eye behavior to that of on-screen moving targets to determine which one the user is looking at. Since Pursuits does not require a precise gaze point, the technique does not require calibrating the eye tracker [Velloso et al. 2017]. Since its introduction, Pursuits has been employed in multiple domains, such as public displays [Khamis et al. 2016b; Vidal et al. 2013], smartwatches [Esteves et al. 2015], VR [Khamis et al. 2018], AR [Esteves et al. 2017], and active eye tracking [Khamis et al. 2017]. Smartwatches and other devices with small screens benefit greatly from Pursuits; pinpointing targets on small screens is not only challenging but also limits the number of simultaneously displayed options. When using Pursuits however, the size of the target is irrelevant as long as it is moving, which allows for a higher entropy of selectable targets. This entropy can be significantly expanded if targets were selectable even if they momentary move out of the bounds of the small screen. For example, think of a target following a circular trajectory whose center is near one of the corners or edges of a smartphone screen; if users are still able to anticipate how the target moves although it is not visible and successfully select it, the number of selectable targets can then be extended. This is one of the aspects that motivated us to explore HiddenPursuits. Another motivation is that there are many applications in which a selectable moving target can be temporarily hidden behind another object. For example, Pursuits can be used to select targets in VR, which are sometimes concealed behind other 3D objects [Khamis et al. 2018].

3 USER STUDY

The goal of this study is to investigate the effect of partially hidden trajectories on the performance of Pursuits.

3.1 Study Design

Our study covered two independent variables with four conditions. We wanted to study the influence of two interleaved variables on the detection accuracy. The first variable is the size of the hidden portion of the trajectory. The conditions of this variable are illustrated in Figure 1; the first condition is the baseline in which the entire trajectory is shown (0% hidden trajectory), while 25%, 50% and 75% of the trajectory was hidden in the remaining conditions respectively. Second, we hypothesize that the duration spent following the moving target before it disappears influence how well the user will follow it while it is hidden. Hence, we further classified the four aforementioned conditions to cover different 'visible distances' before the target becomes hidden; these conditions varied in 12.5% steps ranging from 12.5% to 75% of the cycle. For example, in cases where 50% of the trajectory is hidden, we added conditions such that the trajectory is visible (1) 12.5% of the trajectory before hiding (e.g., appearing at angle 225°and hiding starting angle 270°), (2) 25% of the trajectory before hiding, (3) 37.5% of the trajectory before hiding, and (4) 50% of the trajectory before hiding. To cover all possibilities, the final number of conditions was 13: 25% hidden trajectory with 6 starting positions, 50% hidden trajectory with 4 starting positions, 75% hidden trajectory with 2 starting points, and the baseline in which the target is visible all the time. For each condition, participants followed the moving target as it made two complete 360°cycles. We followed a within-subjects design, in which all participants went through all conditions. Conditions were counter balanced using a Latin-square.

3.2 Apparatus and Study Design

We used a Tobii REX eye tracker (30 Hz) and a 15" Laptop (2880 × 1800). Participants were seated 50–60 cm in front of the display. We extended an eye-based game [Khamis et al. 2015], in which users selected fish using Pursuits. We adapted the game to show one fish at a time moving in a circular trajectory, and depending on the condition, we overlaid an object to hide part of the fish's circular trajectory (Figure 1). The direction of the movement (clockwise or anti clockwise) was determined randomly by the system to reduce learning effects; the hidden portion of the trajectory was adapted to match the condition being tested. The target's speed was 750 pixels per second. This is equivalent to an angular velocity of 90°per second, which is 10.1°of visual angle in our setup. The trajectory's radius was one sixth of the screen width, which means the target takes approximately 4 seconds to complete one cycle.

3.3 Participants and Procedure

We recruited 17 participants (8 females) aged between 20–32 years ($M = 24.5, SD = 3.1$). We first welcomed the participants and asked

Table 1: Median responses to the 5-point Likert scale questions (5=Strongly agree;1=Strongly disagree) indicate that selecting targets whose trajectories are up to 50% hidden are perceived to be easy to select, and associated with medium to high selection confidence.

Hidden trajectory percentage	25%	50%	75%
It was easy to follow the fish	5 (SD = 0.49)	4 (SD = 0.68)	2 (SD = 0.98)
I was confident I am able to follow the fish	4 (SD = 0.75)	4 (SD = 0.97)	2 (SD = 1.19)
It was natural to follow the fish while it was hidden	4 (SD = 0.88)	3 (SD = 1.02)	2 (SD = 1.23)

them to sign a consent form. We explained that the participant's task is to gaze at the moving fish throughout the study. The experimenters verbally announced that the fish will start moving and then pressed the space button to start the movement. Gaze data was collected and stored locally as participants followed the moving fish. We concluded with a questionnaire and semi-structured interview.

4 RESULTS AND DISCUSSION

In addition to the qualitative feedback form the questionnaire responses, we collected quantitative data from: 2 cycles × 13 conditions × 17 participants = 442 trials.

4.1 Qualitative Feedback

As reported in some previous works that involve gaze-based interaction, some participants reported experiencing eye fatigue after multiple selections. Participants said that anticipating the hidden targets' trajectory becomes easier over time. Some participants mentioned they would lose track of the target and then gaze directly at the position it is predicted to reappear at, especially when it is hidden for a long period. Participants generally felt more confident that they are following the hidden target when it was hidden for shorter amounts of time. As demonstrated in Table 1, the perceived easiness and confidence of following the target decreased as the hidden part increased. However, participants generally positiely perceived HiddenPursuits up to 50% hidden trajectory.

4.2 Quantitative data

Due to overheating issues the gaze data collected from P1 and P2 was corrupted and hence discarded. We also excluded the data of P16 due to the eye tracker disconnecting multiple times.

We used the Pearson correlation coefficient since it was shown to be robust to calibration errors and was widely tested in previous work [Khamis et al. 2015, 2016a; Vidal et al. 2013]. Works that employ this approach consider the moving target to be gazed at if the correlation between the target's positions and the user's gaze are above a certain threshold. Similar to previous implementations of Pursuits [Esteves et al. 2015; Khamis et al. 2015, 2017, 2016a; Kosch et al. 2018; Velloso et al. 2017, 2016; Vidal et al. 2013], we use gaze estimates obtained using an *uncalibrated* eye tracker. We used the correlation coefficient to see how far the eye movements deviate from the target's trajectory while it is hiding. Inspired by previous work (e.g., [Khamis et al. 2015, 2016a; Vidal et al. 2013]), we used a window size of 500 ms. All possible windows of 500 ms inside the entire cycle are considered. To avoid overlapping data, we take all gaze points into account that are within 500 ms until the condition switches from hidden to visible or vice versa. This means that all windows include samples where the target was either visible or hidden, but not both.

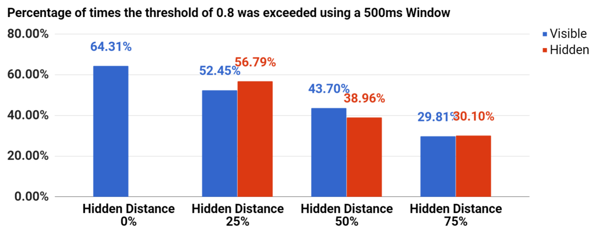

Figure 2: The figure shows the average percentage the correlations that exceed 0.8 using a 500ms time window. This means that HiddenPursuits selection is on average between 1–1.5 seconds. It also shows the reduction in correlations exceeding the threshold as the hidden distances increase, which means that it is likely that longer time will be required until the threshold is exceeded.

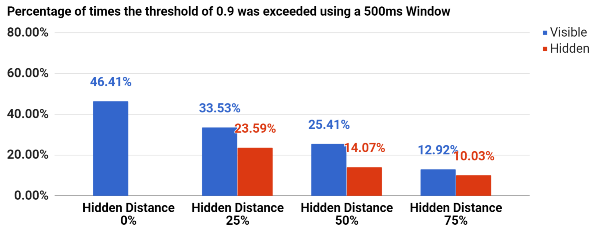

Figure 3: When using a threshold of 0.9, trends are similar to those shown in figure 2 but values are significantly; for example, with with 75% HiddenPursuits, selection would take an average of 10 windows of 500 ms = 5 seconds.

4.2.1 Effect of Hidden Portion of a Target's Trajectory on Selecting it while Hidden. Figures 2 and 3 illustrate the percentage of times the correlation exceeded thresholds of 0.8 and 0.9 respectively when considering windows of 500 ms. If said percentage is 50%, then it means that the threshold is exceeded on average every two windows, i.e., once per second. We distinguish cases where the correlation is calculated while the target is visible (blue bar) and those where it is calculated while the target is hidden (red bar). The baselines in figures 2 and 3 indicate that selection time is between 1 and 1.5 seconds, which is similar to values reported in previous work [Khamis et al. 2015, 2017]. The figures also show that the threshold is exceeded less often as the hidden area increases. For example, Figure 2 shows that while the threshold is exceeded on average once every 2–3 windows in case of hiding 25% of 50% of the trajectory (i.e., 1–1.5 seconds), it is exceeded every 3–4 windows in case of hiding 75% of the trajectory. The values are overall lower when using a higher threshold, which is expected [Vidal et al. 2013]. However the figures indicate that an increase in the threshold also results in a significant decrease in the percentage of correlations exceeding the threshold.

An unexpected result is that in case of 25% and 75% hidden trajectories, the results are slightly more positive when the target is hidden than when the target is visible. A possible explanation is that the random movement direction resulted in a short delay until the participant caught up with the target, which resulted in few gaze points that are off the target. On the other hand, it is less likely this happens while the target is hidden, because the participants always saw the target as it moves behind the obstacle that hides it. Furthermore the difference is very mild and not statistically significant (p>0.05), which means that there is no evidence that selecting targets while they are hidden results in higher correlation values compared to when they are visible.

With the threshold of 0.9 it takes around 4 windows for a target with 25% hidden trajectory to be selected, which means selection would be made every 2 seconds on average. This steadily deteriorates until 10 windows of 500ms in case of a 75% hidden trajectory.

A repeated measures ANOVA with Greenhouse-Geisser correction revealed a significant main effect of the condition on the percentage of time where the correlation exceeded a threshold of 0.8, $F_{1.88,26.31} = 135.5, p < 0.001$. As expected from Figure 2, Post-hoc analysis with Bonferroni correction showed significant differences between all pairs ($p < 0.01$), except for:

- HiddenDistance 50% (hidden) vs HiddenDistance 50% (visible)
- HiddenDistance 50% (hidden) vs HiddenDistance 75% (hidden)
- HiddenDistance 50% (visible) vs HiddenDistance 75% (hidden)

A repeated measures ANOVA with Greenhouse-Geisser correction revealed a significant main effect of the condition on the percentage of time where the correlation exceeded a threshold of 0.9 as well $F_{1.49,20.81} = 84.71, p < 0.001$. As expected from Figure 3, Post-hoc analysis with Bonferroni correction showed significant differences between all pairs (($p < 0.05$)), except for:

- HiddenDistance 25% (hidden) vs HiddenDistance 50% (hidden)
- HiddenDistance 25% (hidden) vs HiddenDistance 75% (hidden)
- HiddenDistance 50% (hidden) vs HiddenDistance 75% (hidden)

From the statistical analysis, we can conclude that the higher the hidden portion, the more significant is the decrease in the percentage of times the correlation exceeds the 0.8 and 0.9 threshold.

4.2.2 Effect of Visible Part of the Trajectory on Selecting Hidden Targets. Another goal of the study was to determine for how long the target’s trajectory needs to be visible before it hides in order for participants to anticipate its movement. Since we let the target run for two full cycles, to answer this question we must only look at the first cycle, because in the second cycle participants already know how the target moves. In our setup, we found that showing the target’s trajectory 25% of a full cycle before hiding it achieves best results. By examining Figure 4, it can be seen that following a hidden target after being visible for 25% of its trajectory results in the highest correlations among hidden targets. Finally, we noticed that following hidden targets is characterized by larger saccadic jumps compared to visible targets.

4.3 Summary

The results indicate that the use of a threshold of 0.8 results in acceptable performance of HiddenPursuits when up to 50% of the trajectory is hidden. Performance is better in case 25% is hidden compared to when 50% is hidden. We also found that displaying the target at least 25% of the trajectory before hiding it makes it easier for users to anticipate its trajectory while it is hidden.

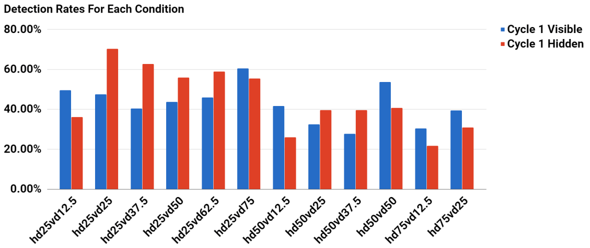

Figure 4: Results using the threshold 0.8. Instead of showing the averages over both cycles as it was done in figures 2 and 3, this graph shows the influence of the visible distance on the correlation per condition within the first cycle. For example hd25vd125 is the condition where the hidden distance is 25% of a full cycle and the visible distance the object is shown before it hides is 12.5%.

The results indicate that the participants were able to anticipate the target’s position even when it is invisible. Through the data analysis, we concluded that the more time users spend to detect the object trajectory with the presence of the object, they more effectively they can anticipate the hidden target’s position. This can be explained by psychology literature that shows that humans can perform smooth pursuit eye movements that anticipate some variations, e.g., in position or velocity [Kowler and Steinman 1979].

5 LIMITATIONS AND FUTURE WORK

We investigated the changes in correlation when a single target was visible or hidden only. In future work, we plan to investigate the case of multiple targets, some of which are hidden. Future experiments should also include negative samples. Another direction for future work is to investigate other trajectories in addition to circular ones, such as rectangular, linear and random trajectories.

Recent work showed that smooth pursuit eye movements change depending on how cognitively overloaded the user is [Kosch et al. 2018]. We expect that the differences between eye movements when following visible and hidden targets can be larger if the user is tired.

6 CONCLUSION

In this work, we explored HiddenPursuits, that is, the possibility of selecting a moving target while it is hidden or after part of its trajectory has been invisible to the user. We found that hiding up to 50% of the trajectory in our setup yields good perceived performance and selections as fast as 1 or 1.5 seconds. HiddenPursuits would be useful particularly in environments where targets are likely to be obscured or hidden by other objects (e.g., in VR) or to expand selection options on small screens by, for example, allowing targets to move temporarily out of the bounds of the screen.

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