# User Perception of Smooth Pursuit Target Speed

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## ABSTRACT

Gaze-aware interfaces should work on all display sizes. This paper researches whether angular velocity or tangential speed should be kept when scaling a gaze-aware interface based on circular smooth pursuits to another display size. We also address the question of which target speed and which trajectory size feels most comfortable for the users. We present the results of a user study where the participants were asked how they perceived the speed and the radius of a circular moving smooth pursuit target. The data show that the users' judgment of the optimal speed corresponds with an optimal detection rate. The results also enable us to give an optimal value pair for target speed and trajectory radius. Additionally, we give a functional relation on how to adapt the target speed when scaling the geometry to keep optimal detection rate and user experience.

## CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *User studies*; **Gestural input**.

## KEYWORDS

circular smooth pursuits; user perception of smooth pursuit speed; optimal smooth pursuit detection.

**ACM Reference Format:**
Heiko Drewes, Sophia Sakel, and Heinrich Hußmann. 2022. User Perception of Smooth Pursuit Target Speed. In *2022 Symposium on Eye Tracking Research and Applications (ETRA '22), June 8–11, 2022, Seattle, WA, USA.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3517031.3529234

## 1 INTRODUCTION

Smooth pursuit eye movements occur when the eyes follow a moving target. Such eye movements are hard or impossible to perform without the stimulus of a moving target [Berryhill et al. 2006; Hashiba et al. 1996]. Since the publication of Vidal et al. [Vidal et al. 2013], smooth pursuits for gaze interaction became a popular research topic, because gaze interaction with smooth pursuits does not require calibration, which is the main obstacle for gaze-aware interaction on public devices. Many publications in this field deal with detection methods and detectability [Drewes et al. 2018; Herlina 2018; Velloso et al. 2018], with possible applications such as entering PIN codes [Cymek et al. 2014], gaze interaction for smart watches [Esteves et al. 2015], smooth pursuit-based widgets [Špakov et al. 2016], control of ambient devices [Velloso et al. 2016], calibration [Drewes et al. 2019b; Khamis et al. 2016; Pfeuffer et al. 2013], object selection [Velloso et al. 2017], and text entry [Lutz et al. 2015]. Further research explored different contexts such as virtual reality [Breitenfellner et al. 2019; Khamis et al. 2018; Piumsomboon et al. 2017] or interaction design issues like feedback [Kangas et al. 2016]. However, research results on users' perception of target speeds are not available yet, according to our literature research. Following the spirit of user-centered design, this research focuses on the user's judgment of target speeds and trajectory sizes of smooth pursuits.

Among all possible trajectories, circular trajectories seem to be well suited for pursuit-based interfaces as their movement is endless and predictable. A continuous movement has the advantage that it does not force the user to accomplish the interaction task within a limited time. Unpredictable direction or speed changes lead to a less matching eye motion [Drewes et al. 2018; Engel et al. 2000; Mrotek L.A. 2006] and consequently lead to lower detection rates. Circular smooth pursuits are prevalent for pursuit-based interfaces. Many publications, for example, Orbits [Esteves et al. 2015], SMOOVS [Lutz et al. 2015], DialPlates [Drewes et al. 2019a], only deal with circular smooth pursuits, and Velloso et al. presented detection algorithms for circular orbits [Velloso et al. 2018]. Therefore, this paper focuses on user perception of circular smooth pursuits.

One open question for pursuit-based interfaces is how to adapt the target speed when scaling the geometry. Scaling the geometry is a frequent challenge in human-computer interaction as we have a vast variety of display sizes. Within the web's context, there is a concept called responsive web design to deal with different display sizes.

Our research question is whether the tangential or angular velocity determines the user perception. Or, in other words, should we keep the tangential speed or the angular velocity of the target when we change the trajectory radius?

**H1**: the target's angular velocity determines the user perception
**H2**: the target's tangential speed determines the user perception

Additionally, we investigated in general, suitable and well perceived target speed for the user in smooth pursuit interfaces, as well as the right size for the trajectory.

## 2 RELATED WORK

Psychology researched smooth pursuit eye movements already in the 50s and 60s [Robinson 1965; Westheimer 1954] and continued the research [Collewijn and Tamminga 1984] until today [Burke and Barnes 2007; Ross et al. 2017; Soechting et al. 2010; Startsev et al. 2019]. For psychology, smooth pursuits are a classification of

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*ETRA '22, June 8–11, 2022, Seattle, WA, USA*

ACM ISBN 978-1-4503-9252-5/22/06…$15.00
https://doi.org/10.1145/3517031.3529234

eye movements, and the research interest is the underlying neural processes. In contrast, for HCI (human-computer interaction) research, smooth pursuits are an interaction technique for gaze-aware interfaces. For interaction, it is less important whether the eyes perform a smooth pursuit movement or some "catch-up" saccades because of fast target movement. For HCI, the interesting questions are whether the users can perform the eye movement, whether they feel comfortable with it, whether the hardware and the software can detect such eye movements reliably, and finally, find possible applications.

The idea to use smooth pursuit eye movements for computer interfaces originates in the publication of Vidal et al. [Vidal et al. 2013] from the year 2013. The main benefit of using smooth pursuits for gaze-based interfaces is that such interfaces work without the eye tracker's calibration. Especially for public interfaces spontaneous interaction is typical and highly desirable [Khamis et al. 2017]. Calibration-free gaze interfaces can enable these spontaneous interaction with displays.

A further advantage of smooth pursuits is the low demand for display space. Most smooth pursuit detection methods are insensitive to scaling and thus allow small trajectories for the target. Esteves et al. demonstrated this by implementing a smooth pursuit interface on a smartwatch [Esteves et al. 2015]. They used eight moving targets on a smartwatch from which a target could be selected by following it with the gaze.

Instead of target selection Špakov et al. used smooth pursuits for continuous input, such as increasing or decreasing the volume while following the target with the gaze [Špakov et al. 2016].

A further application of smooth pursuits is calibration. Pfeuffer et al. showed that it is possible to use smooth pursuits for calibration [Pfeuffer et al. 2013]. They used a target moving on a rectangular trajectory. Khamis et al. used text on diagonal lines for calibration [Khamis et al. 2016]. Drewes et al. researched circular trajectories for calibration purposes [Drewes et al. 2019b]. They showed that the target speed and the trajectory radius influence the calibration quality. However, they studied only two different speeds on two different radii, means four conditions.

In 2018 Drewes et al. researched the optimal speed for circular pursuits, however, only with respect to detectability and without users' perception and only for a fixed radius [Drewes et al. 2018]. The research presented here extends the research on optimal smooth pursuit target speed.

The standard detection method for detecting smooth pursuits is the correlation between gaze and target movement. Meanwhile, there are further detection methods introduced by Velloso et al. [Velloso et al. 2018] and Drewes et al. [Drewes et al. 2019a]. For the evaluation of our study, we used the correlation and the rotated correlation method.

As this research focuses on the human ability to perform smooth pursuit eye movements, the work of Kosch et al. [Kosch et al. 2018] should also be mentioned as it shows that the quality of the smooth pursuit movement depends on the user's mental workload.

# 3 USER STUDY

## 3.1 Design of the User Study

The basic idea for the study was to provide a moving target as a stimulus for the gaze on circles of different sizes and at different speeds. The stimulus was a red circle with 40 pixels diameter (0.8°), big enough to be easily visible and small enough for negligible inner-target gaze movements. Our user study had two independent variables, the radius and the angular speed. The two dependent variables were the ratings of size and speed on a Likert scale.

After offering a stimulus, the study software displayed a dialog where the participant was asked to judge the speed and the radius on a 7-point Likert scale. The possible answers for the speed were: 'much too slow', 'too slow', 'little to slow', 'just right', 'little to fast', 'too fast', 'much too fast'. The possible answers for the size were analogous with 'small' and 'big' instead of 'slow' and 'fast'.

We decided to use five different radii in combination with five different angular velocities, which results in 25 conditions for the participants to judge. We constructed the values for radius and speed by doubling the previous value. The reason for this choice was to get several combinations for the same tangential speed (see Table 1). Table 2 shows the tangential speeds in degrees of visual angle. For the calculation from pixels to degrees we used the average distance to the display estimated later in the user study.

**Table 1: Tangential speeds (pixel/s) for all combinations of angular velocities (cycles/s) and radii (pixels).**

| *velocity (cycles/s)* *radius (px)* | 0.125 | 0.25 | 0.5 | 1.0 | 2.0 |
|---|---|---|---|---|---|
| 25 | 19.63 | 39.27 | 78.54 | 157.1 | 314.1 |
| 50 | 39.27 | 78.54 | 157.2 | 314.2 | 628.3 |
| 100 | 78.54 | 157.1 | 314.2 | 628.3 | 1257 |
| 200 | 157.1 | 314.2 | 628.3 | 1257 | 2513 |
| 400 | 314.2 | 628.3 | 1257 | 2513 | 5027 |

**Table 2: Tangential speeds (°/s) for all combinations of angular velocities (cycles/s) and radii (°). The conversion from pixels to degrees of visual angle uses the average distance to the display measured later in the study (50 pixels correspond to 1° visual angle).**

| *velocity (cycles/s)* *radius (°)* | 0.125 | 0.25 | 0.5 | 1.0 | 2.0 |
|---|---|---|---|---|---|
| 0.5 | 0.39 | 0.79 | 1.57 | 3.14 | 6.28 |
| 1.0 | 0.79 | 1.57 | 3.14 | 6.28 | 12.6 |
| 2.0 | 1.57 | 3.14 | 6.28 | 12.6 | 25.1 |
| 4.0 | 3.14 | 6.28 | 12.6 | 25.1 | 50.3 |
| 8.0 | 6.28 | 12.6 | 25.1 | 50.3 | 100 |

## 3.2 Apparatus

For the study, we used a laptop with a built-in eye tracker (Tobii IS4 Base AC), which delivers eye position data with a 60 Hz rate. The display had a size of 38.4 cm times 21.7 cm (17 inches diagonal). With a resolution of 1920 x 1080 pixels, this means 50 pixels per centimeter or 0.20 mm for one pixel.

The eye tracker was not calibrated to the participants but one of the authors. The whole study was done without any change in the calibration. For offering the stimuli and recording the gaze data, we used a self-developed software for the Windows platform written in C++ with VisualStudio and the TobiiSDK.

For the detection of smooth pursuit movements, we used a sliding data window of 30 samples, which means a time interval of 500 milliseconds and a threshold of 0.8 for the correlation and the rotated correlation method. With 7 seconds stimulus, 3 seconds preparation time, and some seconds for the users' rating, the study lasted less than 10 minutes. We learned from previous studies [Drewes et al. 2018, 2019a] that longer times for pursuit tasks fatigue the users.

### 3.3 Participants & Procedure

We invited 17 participants to the study, 12 males and 5 females, in the age from 26 to 56 years with an average of 30.1 years. Eight of them wore corrective glasses, and one wore contact lenses. All except one person stated that they had at least little experience with eye-tracking, which means they already participated in another eye-tracking study or experienced an eye-tracking demo. Every participant got a brief introduction on smooth pursuits and an example of how the stimulus will look like. After this, we told them to judge the speed and the size of the trajectory after each offered stimulus.

The experiment started with a dialog box where the participants entered their demographic data such as age and gender, their eye tracker experience, and whether they wear corrective glasses during the study.

After filling the dialog, the software started with the tasks. Before displaying the stimulus, the screen showed the text "Please follow the red target with your gaze" for three seconds. This gave the participants a time of preparation to focus on the task. The stimulus was shown for seven seconds. During this time, we recorded the gaze coordinates and the results of two pursuit detection methods. After each stimulus, we displayed a dialog where participants judged the target speed and the trajectory size on a Likert scale from -3 to 3. The procedure was repeated 25 times for all combinations of 5 speeds and 5 trajectory radii. The order was randomized individually for every participant to avoid learning effects.

## 4 EVALUATION

### 4.1 Average Distance to the Screen

Modern eye trackers allow free movement in front of the system and report the eye position relative to the screen. The distance to the screen is needed to convert pixels to visual angles. We estimated the average distance of the participants' eyes to the screen while they filled the on-screen demographic data form. The average distance of the eyes to the screen for all participants was 55.1 cm, with a standard deviation of 5.8 cm. This calculates to a visual angle of $0.020^\circ$ per pixel or 50 pixels per degree. With this factor, all pixel values given in this paper can be converted to degrees of visual angle.

### 4.2 Rating of the Target Speed

Figure 1 shows the target speed rating over angular velocity for different radii. Figure 2 shows the same data over tangential speed. The figures show that the judgment of speed depends on the radius of the trajectory. If the perception of speed would depend only on angular velocities, the data for the different radii would overlap in Figure 1. Analogously, if the perception depends only on tangential speed, the data in Figure 2 would overlap. However, the curves lie above or below another curve. The intersections with the x-axis, which means a Likert-value of zero ('just right'), are different for each radius. To show that the curves lie above each other we applied pairwise Wilcoxon signed-rank tests with continuity correction to our data. The tests revealed significance for most data pairs. The few data pairs which did not show significance were from successive radii. With only three different radii in the study, means the smallest, the middle and the biggest radius, it could be shown that all pairs of values are significantly different.

The answer to whether to keep the angular velocity or the tangential speed when scaling the geometry is neither angular velocity nor tangential speed. This means both hypotheses, H1 and H2, have to be rejected. With a bigger radius for the trajectory and keeping the angular velocity, the users will perceive the speed as too fast; when keeping the tangential speed, the users will perceive the speed as too slow.

The optimal angular velocity, according to the user rating for a certain radius, can be estimated in Figure 1 by the intersection of the rating with the x-axis. To find these values, it is necessary to interpolate from the measured data, for which we used a logarithmic regression, shown as dotted lines in Figure 1. The logarithmic regression is only an approximation and has no theoretical background. Because of this approximation, we were generous with the error intervals and assume an error up to ±0.1. Table 3 shows the estimated values.

### 4.3 Optimal Detection

Figure 3 visualizes the results of the pursuit detection with the correlation method. Again the best detection rate, meaning the maximum detection rate, depends on the speed and the trajectory radius. The detection rate when using the rotated correlation method is depicted in Figure 4 and looks similar; however, the absolute values are higher.

The optimal detection rate is the maximum of the curves in Figures 3 and 4. Again there is no known function for the relation of speed and radius to the detection rate and therefore it is not possible to fit the data to a function. The curves in Figures 3 and 4 are an interpolation and only have the purpose of visualization, but have no theoretical background. However, it helped us to estimate the optimal detection, which is summarized in the last two columns of Table 3. We assume that the error does not exceed ±0.1 except for the 25 pixels radius where the curve is very flat, and an error of ±0.2 seems to be possible.

Figure 5 combines the results of optimal speed and optimal detection ratings. It indicates that optimal user ratings and optimal detection rates coincide. It also suggests a linear approximation on a logarithmic scale (shown as dotted line), from which we can derive a rule of thumb as a design recommendation: when doubling the trajectory radius, the target's angular velocity should be reduced by about 0.13 cycles per second.

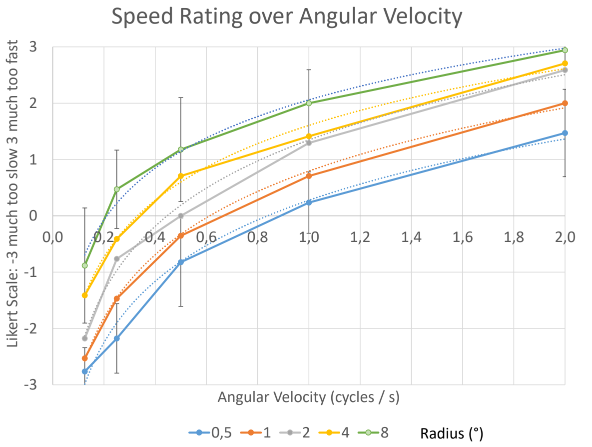

**Figure 1: Rating of target speed over angular velocity for trajectories with different radii. For bigger radii the users prefer lower angular velocities. The optimal speeds are the intersections with the x-axis. The dotted lines are a logarithmic regression for estimating the optimal speeds. For visual clarity the standard deviation as error indicator is given only for the biggest and smallest radius.**

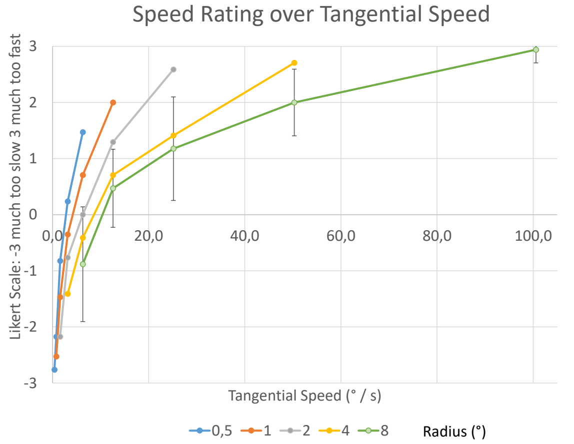

**Figure 2: Rating of target speed over tangential speed for trajectories with different radii. Also if looking at the tangential speed there is a dependency on the trajectory size.**

If the radius $r$ is given by design constraints, for example in the context of responsive web design, the best angular velocity can be calculated from the approximation line in Figure 5 with the following formula:

$$\omega(r) = \omega_{opt} - f * log_2(r/r_{opt}) \quad (1)$$

with $f = 0.13$ cycles/s, $\omega_{opt} = 0.4$ cycles/s, and $r_{opt} = 2.8°$.

Formula 1 is an approximations which enables to calculate an optimal value for the angular velocity within a reasonable range of radii, which is 0.5° to 8.0°. For smaller radii the formula does not

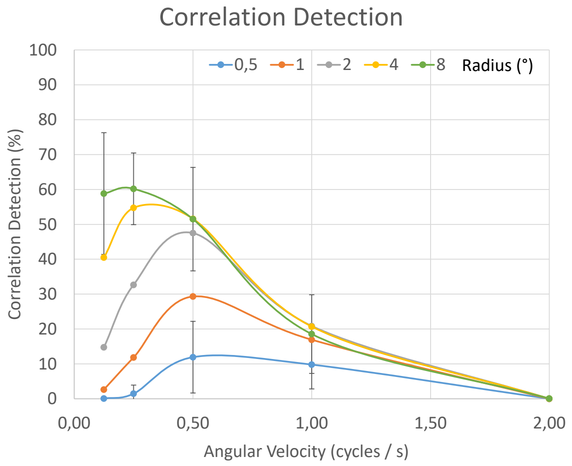

**Figure 3: Results for the correlation detection over angular velocity for different radii. The maximum detection rate depends on the radius of the trajectory. For visual clarity the standard deviation as error indicators are only given for the smallest and biggest radius.**

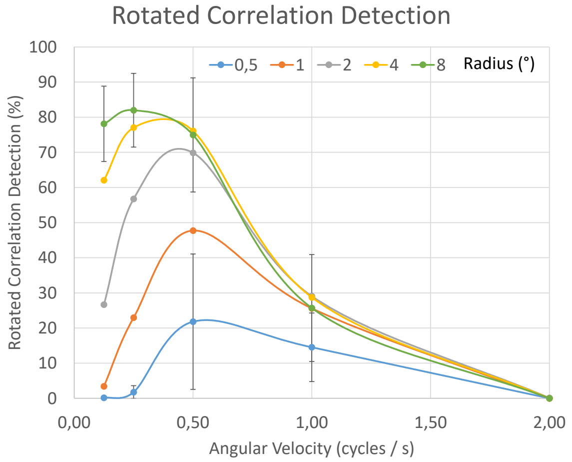

**Figure 4: Results for the rotated correlation detection over angular velocity for different radii. The maximum detection rate depends on the radius of the trajectory.**

make sense as 0.5° is the accuracy limit of an eye tracker. For bigger radii the approximation formula can not be valid, as the angular velocity gets negative for radii above 24°. However, a radius of 24° means a circle with a diameter of 2400 pixels, which exceeds the 1920 x 1080 pixels of the screen. For big radii, where the part of the target trajectory followed by the eye is nearly a straight line, the tangential speed should be kept when increasing the radius. In this range hypothesis H2 is valid.

## 4.4 Rating of the Trajectory Radius

Figure 6 shows the users' rating of the trajectory radius. At first glance, the ratings for each radius are approximately on a horizontal

**Table 3: Optimal angular velocity (cycles/s) for different radii. The values for user rating are the intersections of the lines in Figure 1 with the x-axis. As the values are estimated from interpolation, we assume an error up to ±0.1. The values for the detection methods are estimated from Figure 3 and 4.**

| *radius* | | *optimal ang. velocity (cycles/s)* | | |
|---|---|---|---|---|
| *(px)* | *(°)* | *user* | *Correlation* | *Rot. Corr.* |
| 25 | 0.5 | 0.85 | 0.7 | 0.6 |
| 50 | 1.0 | 0.6 | 0.5 | 0.5 |
| 100 | 2.0 | 0.45 | 0.45 | 0.45 |
| 200 | 4.0 | 0.3 | 0.3 | 0.3 |
| 400 | 8.0 | 0.2 | 0.2 | 0.25 |

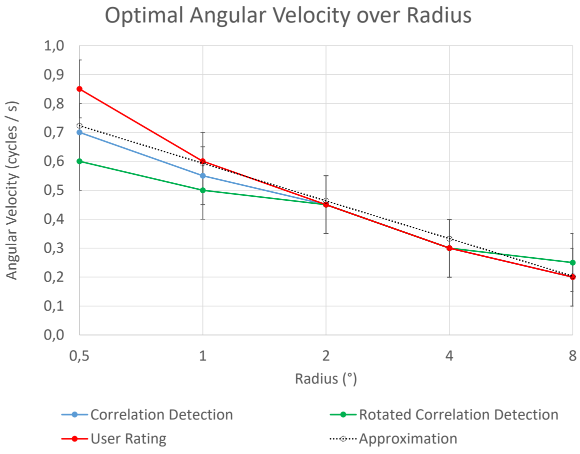

**Figure 5: Optimal angular velocity for different radii based on a) Correlation Detection b) Rotated Correlation Detection c) User Rating d) Approximation. The x-axis is logarithmic.**

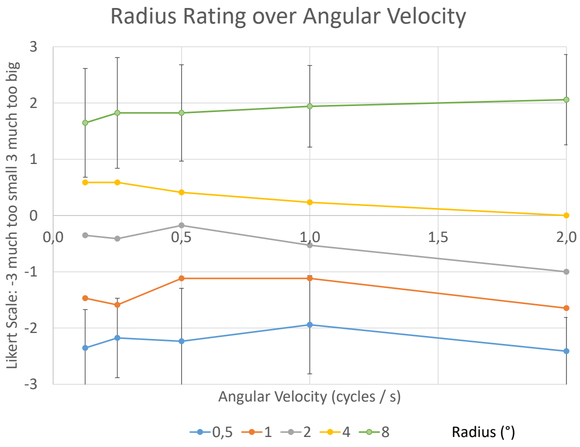

**Figure 6: Rating of target trajectory radius with different radii. For visual clarity error bars (standard deviation) is given only for the smallest and the biggest radius. Every line represents one radius. The 2° (100 pixels) and 4° (200 pixels) radii are close to the Likert value zero ('just right')**

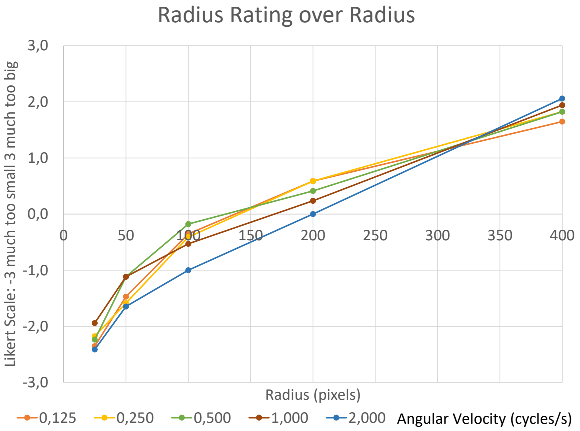

**Figure 7: Rating of target trajectory radius for different angular velocities. As the angular velocity of 2 cycles/s had a detection rate close to zero and the detection rate for the 1 cycles/s was low (see Figure 3), we dropped them for estimating the optimal radius, which is 2.8° (140 pixels).**

line. Target speed has only little effect on the ratings. Trajectory radii with 25 pixels (0.5°) and 50 pixels (1°) are rated as too small, while a radius of 400 pixels (8°) is rated as too large. The ratings for 100 (2°) and 200 pixels (4°) radius are close to 'just right'. As a consequence, we can give the design recommendation for 17 inches displays: Choose a radius for the trajectory between 2° and 4°.

For a more in-depth understanding, we plotted the radius rating over the radius and connected the data points with the same angular velocity with lines (see Figure 7). If the radius rating is independent of angular velocity, the lines should overlap. Figure 7 shows that especially the line for the angular velocity of 2 cycles per second lies a bit aside. The previous section showed that an angular velocity of 2 cycles per second is much too fast and leads to a detection rate of nearly zero percent. This means the 2 cycles per second should not be used and can be neglected.

Figure 7 allows us to estimate the optimal radius much more accurately than Figure 6. The optimal radii are the zeros of the graphs where the Likert-value is 0. If we neglect the blue line (2 cycles/s) and also the dark red line (1 cycles/s) because of low detection rates, we get an optimal radius of 140 pixels (2.8°).

## 5 DISCUSSION, LIMITATIONS AND FUTURE WORK

One result of the study is that whenever the users feel comfortable with the target speed, pursuit detection has the best detection rate. It seems that users feel comfortable when they are able to follow the target with ease. When the target moves too fast, and the user has problems to follow, the detection rate drops. When the target is too slow, gaze jitter outweighs the target movement, causing a low detection rate. The result that user comfort and detectability coincide seems obvious, but it has not been researched or mentioned in literature yet. Furthermore, this result means that previous research on best pursuit detection rates can be seen as research on the best user experience.

Although it was not the topic of our study, it is very likely that the results are also applicable to pursuit calibration [Drewes et al. 2019b; Khamis et al. 2016; Pfeuffer et al. 2013]. We assume that an optimal detection rate also leads to an optimal calibration quality. An optimal detection rate means that the user is able to follow the target with the gaze more accurately than it does for lower detection rates. If these eye movements are used for the calculation of calibration parameters, we expect that it makes an impact on the calibration quality.

The result for the best trajectory radius should be taken with care. This value may depend on the size of the display. The value for the optimal trajectory radius from this study is higher than the size of a small smartphone display, and, consequently, a study on a smartphone display will not lead to the same value. We assume that a user perceives a pursuit trajectory as too big if the target moves too close to the screen's edge. Therefore it would be interesting to do a similar study on a (small) smartphone display and in a virtual reality environment with no limiting edges in the field of view.

During previous user studies, participants reported that following a smooth pursuit target needs much concentration and can be tiring. It would be interesting to explore whether an optimal target speed and trajectory size reduces these effects and makes pursuit-based interfaces less demanding.

## 6 CONCLUSION

The study answered our research question on how to adjust the target speed when scaling the smooth pursuit interface's geometry. It is neither the angular velocity nor the tangential velocity, which should be kept. When increasing the radius of a circular pursuit trajectory, the angular velocity should be decreased. A rule of thumb for the relationship between both parameters is: when doubling the trajectory radius, angular velocity should be reduced by 0.13 cycles/s.

The presented results show that users have a preference for the speed of a smooth pursuit target. This preference seems universal for all users, as the standard deviation in the users' judgment is small (below 8% on a 7-point Likert scale). Users prefer also a certain radius for circular trajectories. Therefore it is possible to give design recommendations in the context of a desktop display. In the case of free choice for a pursuit-based interface, the radius of a circular trajectory should have a size in a range between 2° and 4° with an optimum of 2.8°. The target should move with around 0.4 cycles per second. If the radius is given, formula 1 allows to calculate the optimal angular velocity.

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