Measuring Velocity Perception Regarding Stimulus Eccentricity

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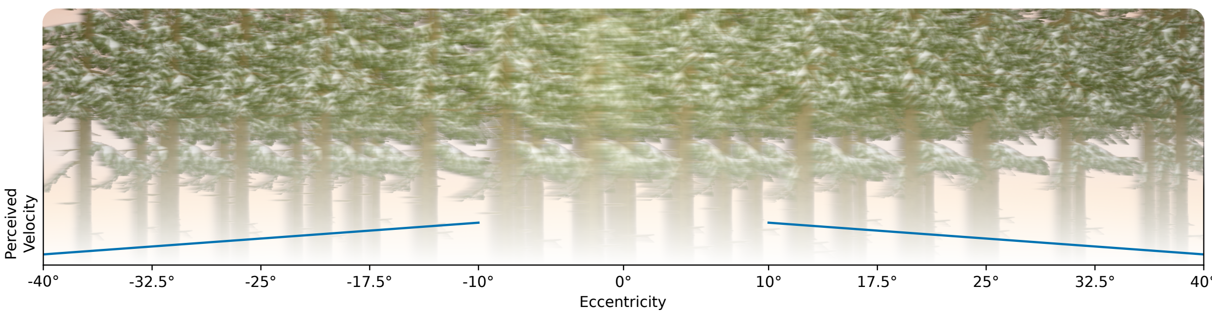

Figure 1: We create an empirical model of velocity perception (relative to the fovea) in relation to eccentricity and physical speed of a stimulus. Blur is used in this visualization to indicate higher perceived velocities, which decrease with eccentricity. The model is linear in the eccentricity dimension θ for a fixed temporal frequency ω as indicated by the blue lines, while exhibiting non-linearities in ω and the combined term $\theta \cdot \omega$. Overall, our results indicate that the perceived velocity of a stimulus decreases with eccentricity for fast-moving stimuli, while this relationship is reversed for slow-moving stimuli.

ABSTRACT

A major factor resulting in cybersickness is the feeling of self-motion experienced when viewing a moving scene in Virtual Reality (VR). Current research indicates that this effect is largely created by motion in the periphery. To discover why this is the case, we investigate the influence of temporal frequency and eccentricity of a stimulus on the magnitude of perceived velocity in the periphery. Based on the perception of two-dimensional stimuli on a wide field-of-view display, we build a model to predict the scaling factor by which the perceived velocity of visual patterns deviates from the physical velocity. Further, our exploratory findings indicate no impact of gaze type on the results, suggesting our model works for both fixation and smooth pursuit scenarios. In an additional pilot study in VR, we test the accuracy of the model to predict unnoticeable object motion adaptation in 3D virtual worlds and find positive indications for a similar effect.

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CCS CONCEPTS

• **Computing methodologies** → **Perception**; *Virtual reality*; • **Applied computing** → *Psychology*.

KEYWORDS

Vection, Cybersickness, Virtual Reality, Velocity Perception, Stimulus Eccentricity

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1 INTRODUCTION

The perception of the world around us is governed by a complex interplay of all our senses. Human vision plays a particularly special role in this relationship — visual information is rich and covers a wide angle. Our brain relies predominantly on visual signals in situations with ambiguous information. Through this prioritization, optical illusions can easily arise when the visual information is not representing the actual state of the real world. One particularly convincing illusion that arises from visual motion information is vection.

Vection is a visually induced effect where the perceived motion (*e.g.*, on a screen) is interpreted as self-motion [Hettinger et al. 1990]. Consider the following scenario: A person is watching a recording from within a race-car on the TV in close proximity to the screen. The screen will cover most of their visual field and the motion information they perceive is mostly contributed by the race-car recording. In this situation, the feeling of moving with the car may arise in the observer despite being physically at rest. This effect is especially pronounced in Virtual Reality (VR), where it can cause severe negative symptoms in the user, referred to as cybersickness [Keshavarz et al. 2014]. Reducing this effect is a key factor to make VR a more pleasant experience for its users and to increase the acceptance of the technology by the general public.

Understanding the precise impact of visual information in different parts of our field of view on the development of vection illusions is essential to actively control the impact of self-motion effects. Many works already indicate that vection is predominantly evoked by peripheral stimuli [Berthoz et al. 1975; Brandt et al. 1973; Keshavarz and Berti 2014; McManus et al. 2017]. Accordingly, the reduction of the field of view in VR scenarios proved to be an effective way to reduce cybersickness [Adhanom et al. 2020; Groth et al. 2021a,b]. However, extensively shrinking the visual field also significantly alters the VR experience. Subtle methods would require a more in-depth understanding that explains the contribution of the velocity of moving objects at different eccentricities on the global perception of scene motion.

However, to the best of our knowledge, the relationship between the eccentricity of a stimulus and the perceived object velocity remains an unexplored characteristic. Furthermore, many confounding factors have been reported in the literature, leading to varying results and uncertainty regarding the peripheral dominance of vection [Hassan et al. 2016; Palmisano and Gillam 1998; Palmisano and Kim 2009; Post 1988; Tarita-Nistor et al. 2006].

In this work, we explore the perception of movement speed of peripheral presentations at different velocities, eye movement behaviours, and eccentricities. For this purpose, we pose the following research questions:

- (RQ_1) Is the velocity of an object perceived differently at different eccentricities?
- (RQ_2) How are stimulus eccentricity and perceived velocity in correlation with one another?
- (RQ_3) Does the type of eye movement (fixation or smooth pursuit) impact the perception of peripheral object speed?
- (RQ_4) Are the results of monoscopic screen scenarios transferable to stereoscopic VR environments?

To answer these questions, first, we perform two experiments with a simple comparison task on a wide field of view monitor. The first experiment investigates the relationship between stimulus eccentricity and perceived object velocity. In the second experiment, we examine to what extent the results differ under certain eye movement scenarios. With the results of these two experiments, we derive an empirical model that describes the relationship between perceived and actual object velocity based on the eccentricity of the object and the temporal frequency of the movement. In a final pilot study in VR, we further explore the applicability of the model for stereoscopic viewing scenarios.

2 RELATED WORK

Vection describes the illusory effect wherein visually perceived motion is interpreted as self-motion [Hettinger et al. 1990]. However, not all visual stimuli produce vection equally. In this section, we explore previous research characterizing the relationship between different variables on the occurrence of vection.

Early research by Brandt et al. [1973] and Berthoz et al. [1975] indicates a dominant effect of peripheral vision on vection. In their experiments, Brandt et al. [1973] covered parts of the visual field while rotating a drum around participants. This resulted in a rotating visual stimulus with participants being at rest. Even with large parts of the central visual field covered, vection occurred, while vection was not reported when the peripheral field was occluded. Berthoz et al. [1975] conducted experiments using linear stimuli visible only in the periphery. The vection produced by these peripheral stimuli outweighed the perceived self-motion from participants being in a moving cart. This effect is further supported by the work of other researchers, such as Keshavarz and Berti [2014] who, in addition to collecting subjective data on participants' experience of vection, also collected event-related brain potential data. The authors claim that the perception of vection is a result of the visual integration of foveal and peripheral vision, based on their experiments with central and peripheral patterns moving in opposite directions.

However, other research contradicts this theory. Post [1988], as well as Nakamura and Shimojo [1998], claim that vection depends on the stimulus area on the retina. Bardy et al. [1999] also failed to find any eccentricity dependence in their experiment investigating the perception of vection during walking with lamellar, radial, or mixed optical flow presented to participants.

McManus et al. [2017] investigated the effects of object motion on vection at different eccentricities within the human visual field including the far periphery at eccentricities above 90°. For this purpose, they occluded different areas on a large-field display and asked participants to move through a hallway to the exact location of a previously seen object. Participants were better able to judge their movement when only the far periphery was visible. In all other scenarios, participants underestimated their movement, leading to overshooting of the target position. In addition to providing evidence for the peripheral dominance of vection, their experiment showed no evidence for an area dependence of self-motion perception.

Researchers have also investigated other variables which could affect the results of experiments to determine the effects of stimulus eccentricity on vection. Research by Palmisano and Gillam [1998] indicates an eccentricity dependence of circular vection in relation to the spatial frequency of the used pattern. Higher frequencies resulted in stronger vection when perceived in the fovea, with lower frequencies being more effective at higher eccentricities. The researchers attribute this to participants being more likely to perceive higher frequencies as distinct objects in their peripheral vision instead of to self-motion.

Hassan et al. [2016] demonstrated how the luminance of a pattern influences the perceived speed of objects at peripheral and central eccentricities. Their results indicate that objects at high luminance appear slower in the peripheral vision of participants even

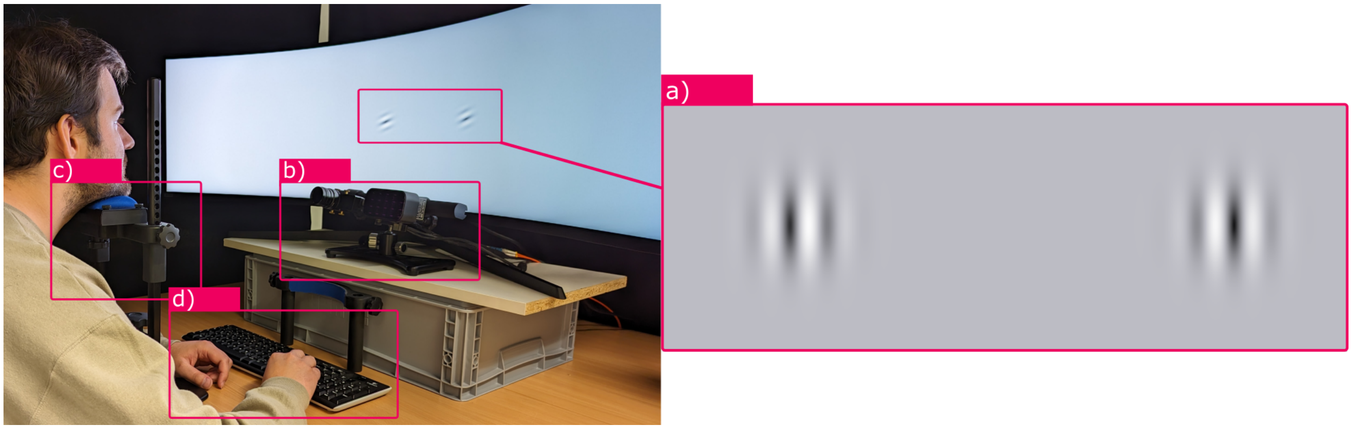


Figure 2: Main experiment setup, showing the two Gabor patches (a) used as stimuli, creating the effect of motion by continuously incrementing the phase of the contained sine wave at a given speed ω. The eye tracker (b) ensures that participants do not observe the peripheral patch directly. To ensure accurate tracking, participants placed their head on a headrest (c). By adjusting the speed of the center patch using a keyboard (d), participants provide empirical measurements for the perceived speed of the peripheral stimuli.

after correcting for perceived contrast. This holds true for lower luminance as well, with the exception of fast-moving objects whose speed participants overestimated at higher eccentricites instead.

Palmisano and Kim [2009], as well as Tarita-Nistor et al. [2006], found a correlation between the gaze type and eccentricity dependence of vection. Their results indicate that presenting participants with a permanent fixation target decreases the amount of vection perceived in the periphery (with vection being equal to the central vision), while only showing the fixation target at the start of the experiment increases vection experienced in the peripheral vision.

Our goal in this paper is to build on these results and improve our understanding of vection. Previous research on this phenomenon relies on subjective measurements of the effect, or measurements of biological responses to vection (such as postural sway) to estimate its strength. This is sufficient to compare different sources of vection, but does not fully describe the effect. We aim to provide empirical measurements of perceived object velocity at varying eccentricities. This way we intend to quantify the effect allowing us to propose an empirical model describing object velocity in relation to stimulus eccentricity.

3 MAIN EXPERIMENT

Our initial goal is to confirm whether a relationship between stimulus eccentricity and the perceived velocity of an object exists, and to characterize this relationship mathematically. For this purpose we performed a perceptual experiment to measure perceived velocities at different eccentricities.

3.1 Experimental Design

We investigate the relationship between stimulus eccentricity and perceived velocity of an object by presenting participants with stimuli at different eccentricities while observing and matching a central stimulus. This allows us to obtain a mathematical relationship between the stimulus eccentricity and the perceived speed as a factor of the physical speed. That is, given an angular speed ω and an eccentricity θ, we determine the ratio of the perceived speed to the real speed $\omega_{perceived}/\omega$.

Stimuli. Participants are presented with two Gabor patches (see Fig. 2). One such patch is shown in the center of the screen, while the other is offset to the left/right at distances $\theta \in \{10.0°, 17.5°, 25.0°, 32.5°, 40.0°\}$. The largest eccentricity was chosen to allow the full extent of the Gabor patch to be shown on the screen without being cut off. To ensure no unintentional bias is added, the direction in which the second patch is offset is counterbalanced among all participants. The orientation of patches was chosen in 40 degree intervals which are randomly distributed among trials to investigate directional bias. The central and peripheral Gabor patch are always oriented in the same direction.

The peripheral Gabor patch is set into motion by incrementing the phase of the contained sine wave by $\omega \in \{2\pi/s, 13\pi/s, 24\pi/s\}$. The maximum value of $24\pi/s \Leftrightarrow 12Hz$ was chosen in tandem with the spatial frequency of approximately 1 cycle/degree to be half the threshold speed that can be perceived at the given eccentricity according to the contrast sensitivity function [Mantiuk et al. 2022]. This ensures a participant's judgment of the speed cannot be skewed due to spatial or temporal aliasing [Mantiuk et al. 2021]. Further influencing our choice, these values provide a good balance between the number of repetitions within each patch and the possible range of speeds. Similarly, the central Gabor patch is also set into motion, but at a speed 1.5 times higher/lower than the peripheral patch. This again is counterbalanced to avoid any bias. This speed is adjustable by the participant.

During the entire experiment, participants are unable to observe the peripheral Gabor patch directly. We ensure this by using an eye tracker to blank the entire screen when a participant is no longer looking at the central Gabor patch. This way, the peripheral motion is always shown at the intended eccentricity, with no way for participants to accidentally observe the patch directly. In addition, we recorded raw eye tracking data for further analysis in Section 5.2.

Participants. For this experiment, we recruited a total of 32 participants (10 female) between the ages of 21 and 39 (mean age 25.84). Participants were university students recruited through the use of a university mailing list. The only requirements for participation were normal or corrected-to-normal vision, and lack of medical preconditions such as photosensitive epilepsy to ensure the safety of participants. The experiment was approved by the corresponding ethics committee. Each participant performed 45 trials, for a total amount of collected trials of 1440 with 96 repetitions for each variable combination. Every participant received a compensation of 5€ for their participation.

Apparatus. The two Gabor patches are shown on a 49" screen with an aspect ratio of 32 : 9 and a curvature of 1000 *R*. This allows us to test eccentricities of up to 40°. To ensure the results are not affected by temporal aliasing the monitor provides a 240 Hz refresh rate. In addition, we utilize an SR Research EyeLink 1000 eye tracker (providing 1000 Hz eye tracking) to ensure both Gabor patches are hidden as soon as the participant's gaze deviates from the center patch. This is especially important, as participants frequently reported accidentally looking towards the peripheral patch. Without the use of an eye tracker to prevent this, this would lead to many trials being invalidated.

Procedure. Before taking part in the experiment, each participant was briefed on the experimental procedure and provided with a consent form including warnings about photosensitive epilepsy and potential discomfort. We also assured participants that if they felt uncomfortable the experiment could be interrupted at any point. Thankfully none of the participants needed to make use of this. The participant's head was then placed on a headrest 64 cm in front of the screen and the eye tracking device was calibrated to ensure stable eye tracking during the experiment. After this, the participant was presented with the stimulus and instructed to use the keyboard to adjust the speed of the central Gabor patch to match that of the peripheral Gabor patch. Once the participant was sure that the speeds match, they confirmed this using the keyboard. Every five trials, a moving target was presented to reduce eye strain as a result of constant fixation on the central Gabor patch. No data was collected during these breaks, as following the moving target was not mandatory. There was no time limit imposed on the participants resulting in an average trial time of 22.9 s. No participant took more than 45 min to complete the full experiment, with the average completion time being just over 17 min.

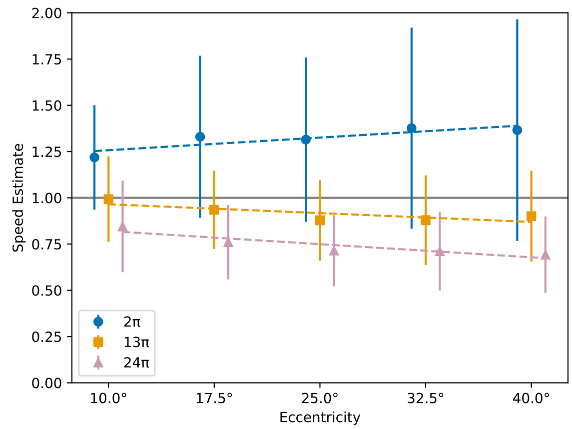


Figure 3: Results from the main experiment, split by temporal frequency. *Speed Estimate* refers to the mean quotient $\omega_{perceived}/\omega$ of the perceived speed over the real speed shown in the peripheral Gabor patch, with error bars representing the standard deviation.

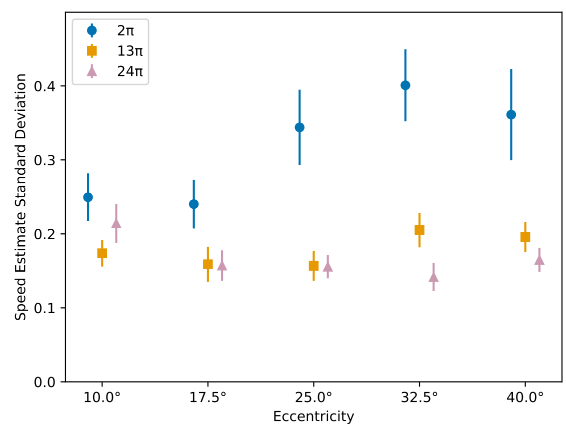
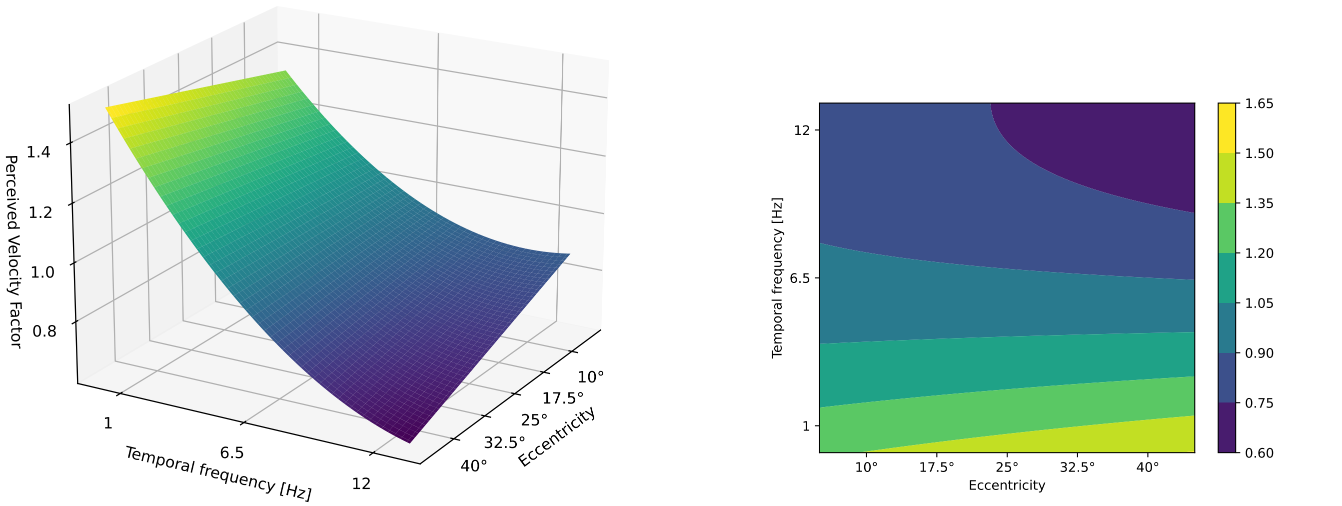


Figure 4: Mean participant variability in our main experiment, measured as the standard deviation over all repetitions per person using the same variables, of the quotient $\omega_{perceived}/\omega$. Error bars represent the standard error of the mean.

3.2 Analysis of the Main Experiment

For the result analysis, we primarily investigated the mean ratios of the perceived velocity to the presented velocity $\omega_{perceived}/\omega$ as this tells us how strongly on average the perceived velocity deviates from the presented velocity. Furthermore, we also examined the standard deviation as this gives us an approximate range within which participants do not perceive a difference to the presented velocity.

Figure 3 shows the results of the main experiment. Importantly, this highlights that an eccentricity dependence of the perceived speed only emerges when looking at the tested temporal frequencies separately. This is because the perceived velocity not only depends on the eccentricity of the stimulus, but this effect changes depending on the velocity of the stimulus itself. Concretely, for slower speeds the velocity is overestimated the further the stimulus lies in a participant's periphery, whereas for faster speeds the velocity of the stimulus is underestimated. To confirm these trends, we perform ANOVA tests. For angular speeds of 13π and 24π, these tests produce significant p-values of $p_{13\pi} = 0.034$ and $p_{24\pi} = 0.019$



(a) 3D surface plot of model predictions

(b) Heatmap showing contours of model prediction ranges

Figure 5: Visualization of the model predictions. Note the shape of the plots, with the effects of increasing eccentricity being flipped at low / high temporal frequencies.

meaning that it is very unlikely that the eccentricity dependence occurred through pure chance. Likely due to the high variance of trials using a temporal frequency of 2π, the p-value for these trials is not significant with $p_{2\pi} = 0.398$.

We also analyzed other factors, such as the orientation of the patch or the gender of participants, but found no significant influence on the results.

Lastly, we investigate the response variability for each participant shown in Fig. 4. This way we can estimate the range of velocities around the previously determined mean that is perceptually identical to the original speed. One limitation of the experiment is the high variability of the lowest temporal frequency. In the future we hope to improve upon this by allowing participants to make finer adjustments at lower speeds. Of note however is the relatively consistent variability of the other two speeds, implying that this is not a problem for higher speeds. Even when examining the worst-case value, this implies that any speed within about 14% of the previously determined mean is perceptually indistinguishable from the original speed.

4 MODELING PERCEPTUAL VELOCITY

To obtain a mathematical model describing our findings, we performed an Ordinary Least Squares regression [Chumney and Simpson 2005]. The resulting model that best fits the data is shown in Eq. (1). The eccentricity θ is given in radians and the angular velocity ω is given in radians / second. The resulting R^2 value accounting for all trials is 36%. The mean deviation from our experimental results is no more than 2.6%, with the largest delta being no larger than 6%.

$$\omega_{perceived}/\omega = 0.25\theta - 0.013\omega + 0.0001\omega^2 - 0.0077\omega\theta \quad (1)$$

Figure 5 shows plots of the model. Importantly, this shows that a linear model would not be sufficient to fit the experimental data, since the relationship between eccentricity and perceived speed changes depending on the actual speed. This explains the need for the $\omega\theta$ term as this allows the speed ω to adjust the strength of influence coming from the eccentricity θ. Of note also is the squared velocity term, which despite the small coefficient becomes increasingly more important with larger velocities. For instance, at our largest used speed of $24\pi/s$, the term grows to 56%.

One important caveat is that the model cannot simply be extended past the eccentricities used in our main experiment. For instance, at $\theta = 0°$, the factor should be trivially 1.0 (as the center represents the reference point). This is not accurately reflected by the model, suggesting that the model does not apply to foveal vision.

5 INFLUENCE OF FIXATION ON MOTION PERCEPTION

Both Palmisano and Kim [2009], as well as Tarita-Nistor et al. [2006], found that presenting participants with a permanent fixation target influences the amount of vection reported. To investigate whether

Figure 6: Two Gabor patches with overlaid fixation cross to study the effects of gaze type on the relationship between eccentricity and perceived speed.

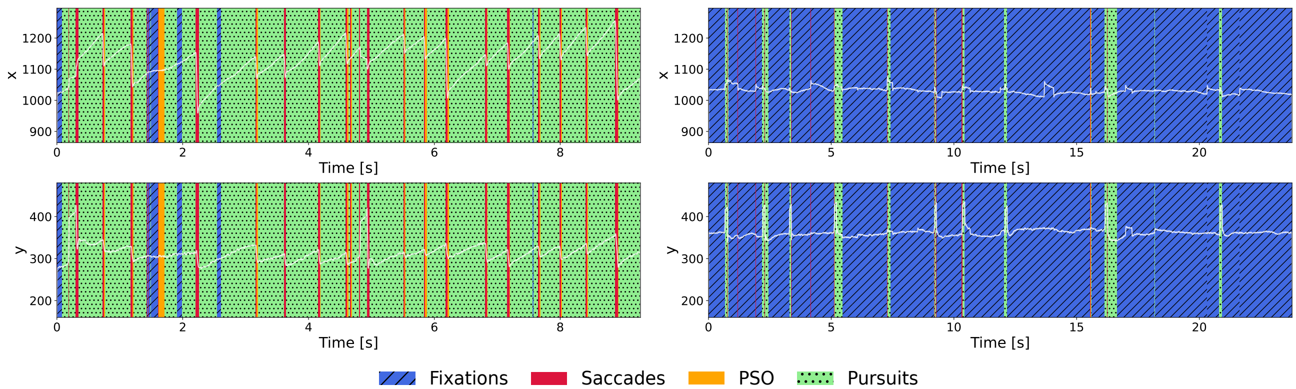


Figure 7: Eye movement classification of trials from the main experiment (left) and the pilot study (right) obtained by running the *NSLR-HMM* eye movement classification method proposed by Pekkanen and Lappi [2017]. Gaze coordinates given in pixel coordinates, with the stimulus centered at $(1080, 320)$.

this effect also applies to general motion, we conduct a pilot study with a subset of participants from the main experiment.

5.1 Experimental Design

To investigate the influence of gaze type on the model, we repeat select trials of the main experiment while showing a permanent fixation target in the middle of the central Gabor patch. The resulting visual is shown in Fig. 6. The following will only discuss differences to the experimental setup described in Section 3.1.

Stimuli. We show two Gabor patches similarly to the main experiment with the eccentricity set to $\theta = 32.5^\circ$ and the temporal frequency set at $\omega = 13\,\pi/\mathrm{s}$. To ensure participants keep their gaze fixated on the center Gabor patch (instead of following the lines within it), we place a brightly colored fixation cross above it. This occludes only a small part of the Gabor patch to ensure the motion stays well visible. To show that this setup results in different gaze patterns compared to the main experiment, we again collect raw eye tracking data for further analysis in Section 5.2.

Participants. For this study, we collected a total of 50 trials over 10 volunteers, including 9 male and 1 female volunteer, with ages ranging from 23 to 36 (mean age of 29.1).

Procedure. Due to the lower number of trials, it is important that participants are immediately familiar with the task. Because of this, the pilot study was performed immediately after the primary experiment. The remaining procedure is equivalent to the main experiment. In total, no volunteer took longer than 5 minutes, with the average completion time being just over 2 minutes.

5.2 Analysis of the Influence of Gaze Type

We evaluated eye movement patterns both qualitatively and quantitatively to ensure the validity of our experiments. During the experiments, we qualitatively evaluated the eye movement patterns as reported in real time by the eye tracking device. This is important for two reasons: We could confirm that eye tracking was functioning correctly, ensuring the stimulus would be hidden if a participant's gaze deviates from the center Gabor patch. Secondly, this allowed us to confirm that, during the main experiment, all participants were exhibiting smooth pursuit eye movement (interrupted periodically by saccades in the direction opposite of the stimulus motion). Contrarily, during the pilot study, we found the participants' gaze to be fixated approximately on the fixation cross, exhibiting no or infrequent smooth pursuit eye movement.

To confirm these qualitative observations, we used the *NSLR-HMM* eye movement classification method proposed by Pekkanen and Lappi [2017]. The full results can be seen in Table 1, with exemplary classifications for individual trials being shown in Figure 7. While Pekkanen and Lappi report low human agreement with their method when distinguishing smooth pursuit and fixation, the results mostly agree with our manual observation.

Having confirmed the difference in eye movement patterns between the two experiments, we want to investigate if this results in a change to the experimental results. To this end, we compare the results of this second experiment to all matching trials (same eccentricity and temporal frequency) of the main experiment using a t-test. This results in a p-value of $p = 0.26$, indicating no statistically significant difference between the means of the experiments.

Because of these observations, we believe the model presented in Section 3.2 to be valid even in situations where the observer is fixating on a point rather than following the stimulus motion.

Table 1: Comparison of the ratio between eye movement classes (Fixation, Saccades, Post-Saccadic Oscillations & Smooth Pursuit) observed during the main experiment and the pilot study. Values obtained by running the *NSLR-HMM* eye movement classification method proposed by Pekkanen and Lappi [2017].

Experiment	Fixation	Saccades	PSO	SP
Main (Section 3.1)	23.7%	4.5%	2.4%	69.4%
Pilot† (Section 5.1)	81.2%	1.6%	0.6%	16.7%

(†) Percentages do not add up to 100% due to truncation.

Figure 8: Setup for the VR pilot study. Participants view one central window surrounded by two peripheral windows in VR. The peripheral windows are placed at an eccentricity of $\theta = 32.5^\circ$ to ensure full visibility in the headsets field of view. Behind each window is a group of trees which is set into motion. Each of these groups is separate to allow differing physical velocities in each window. Participants used a keyboard to indicate when they felt the velocities diverging.

6 VR PILOT STUDY

To find out whether the effects studied in the main experiment apply to more complex scenes, we perform a further pilot study in VR. This allows us to investigate the influence of factors such as depth perception and scene complexity on the relationship between stimulus eccentricity and speed perception.

6.1 Experimental Design

The starting point for the pilot study are the findings of the main experiment. This allows us to investigate if the empirical model holds in VR.

Stimulus. We present participants with a room containing one central and two peripheral windows to the left and right of the observer like shown in Fig. 8. Using eye tracking we again ensure that the peripheral windows are observed at an eccentricity of $\theta = 32.5^\circ$. To indicate motion to the observer, trees move past the windows. The angular velocities of the trees match those of the main experiment (see Section 3.1), with the velocity of the center window starting at an offset equal to the determined ratio $\omega_{perceived}/\omega$. To also test the null hypothesis (i.e. that $\omega_{perceived} = \omega$), we include additional trials with no starting offset. During a randomly chosen initial period of time, the velocities stay constant. This allows participants to indicate if the starting velocities do not match perceptually. After this period of time, the trees behind the center window speed up or slow down.

Participants. We conducted the experiment on 10 volunteers (9 male, 1 female) totaling 360 trials (30 repetitions for each combination of variables), with ages ranging from 21 to 36 (mean age of 28.57). All participants had prior experience with VR and are experts in the field of Computer Graphics. This is to ensure that any observed effect does not disappear with familiarity to the technology. The population consisted mainly of graduated university students recruited via word of mouth. All participants reported normal or corrected-to-normal vision, and lack of medical preconditions such as photosensitive epilepsy. Like the previous two experiments, the study was approved by the corresponding ethics committee, and the participants signed an informed consent form.

Apparatus. Participants viewed the scene through a Meta Quest Pro VR headset offering a resolution of 1800×1920 per eye with a horizontal field of view of 106° and a refresh rate of 90 Hz. The headset includes an eye tracker which again allows us to hide the stimulus in case a participant's gaze deviates from the center window.

Procedure. After putting on the VR headset, the view is centered on the central window. Participants are then instructed to indicate the moment they feel that the speeds of the three windows no longer match. In between trials, we display a blank screen to ensure the participant's perception is properly reset before the next trial. To ensure participants understand the task correctly, the initial five trials are used as practice and do not count towards the results. By inspecting the resulting speeds we then determine a new mean perceived speed $\omega_{perceived}$ and compare it to the results of the main experiment.

6.2 Analysis of the VR Pilot Study

Figure 9 shows the center of the mean range of angular velocities $\omega_{perceived}$ perceived by participants as identical to the actual speed ω. The strong correlation between the chosen starting offset (the mean determined in the main experiment or 1.0 for the null hypothesis) indicates that the experimental setup is not adequate to properly confirm or reject the findings of the main experiment. These issues are further discussed in Section 7.

However, of note is that the results of the VR pilot study for 6.5 Hz and 12 Hz significantly deviate from the findings of the main experiment. This indicates that the model described in Section 4 may not fully apply to the VR scene tested in this experiment. Furthermore, Table 2 shows that participants frequently felt that the initial starting speeds did not match when the central motion was offset by the mean determined from the main experiment. A possible explanation for this is the influence of unexplored variables, such

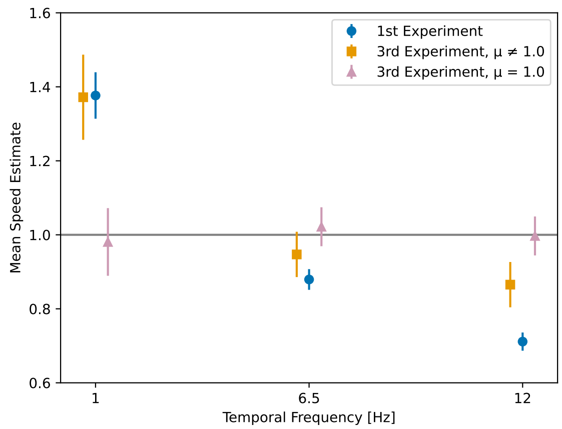


Figure 9: Results of the VR pilot study compared to the initial experiment, showing the mean quotient $\omega_{perceived}/\omega$. Error bars represent the standard error of the mean.

Table 2: Amount of trials from the VR pilot study for which participants indicated that the initial starting velocities did not match.

Mean	ω	# Indicated	% Indicated
1.00	1.0 Hz	9/60	15.0%
1.00	6.5 Hz	1/60	1.7%
1.00	12.0 Hz	0/60	0.0%
1.38	1.0 Hz	24/60	40.0%
0.88	6.5 Hz	1/60	1.7%
0.71	12.0 Hz	10/60	16.7%

as the spatial frequency of the stimulus (as suggested by Palmisano and Gillam [1998]) or the impact of depth perception on the results.

7 DISCUSSION

The experiments we conducted successfully answer our research questions, while also indicating the need for future research to further investigate the perception of peripheral motion. Below, we discuss the insights we gained on our research questions.

(RQ_1) Is the velocity of an object perceived differently at different eccentricities? Through our main experiment we showcased that the perceived velocity of an object depends on the eccentricity within an observer's field of view. Further, the experiment highlights that this relationship is not simply linear, but depends on other factors. Depending on the physical speed of the object, this results in a positive relationship for slower speeds (i.e. slow-moving objects in the periphery are overestimated) or a negative relationship for faster speeds (i.e. fast-moving objects in the periphery are underestimated).

(RQ_2) How are stimulus eccentricity and perceived velocity in correlation with one another? The results from our main experiment not only manage to show that such a correlation exists for stimuli on a 2-dimensional surface, but they also led us to formulate a mathematical model to predict the perceived velocity using the physical speed of the object and the eccentricity of the stimulus in an observer's field of view.

(RQ_3) Does the type of eye movement (fixation or smooth pursuit) impact the perception of peripheral object speed? Using the results of the second experiment, we showed that the gaze type (fixation or smooth pursuit) does not significantly impact our model. This implies that our model works regardless of gaze type.

(RQ_4) Are the results of monoscopic screen scenarios transferable to stereoscopic VR environments? We found positive indications that this effect also exists in VR. However, our model does not fully explain our findings in the VR pilot study. This indicates that there may be other factors involved in the perception of velocities in the periphery.

The results of the main experiment indicate that participants were unable to accurately determine the speed of peripheral Gabor patches for slower temporal frequencies. While this may be an indication that low velocities are harder to distinguish in general, we cannot rule out the possibility of this discrepancy arising from our chosen step sizes. This may lead to inaccuracies concerning the results of the lowest temporal frequencies (1 Hz), affecting the predictive strength of the model at lower velocities. However, this has no impact on the higher two speeds, or the general trends we observed.

Furthermore, the results of the VR pilot study indicate that the starting velocity of the central window unintentionally influenced the results. This makes it hard to conclusively tell if our model is adequate to describe VR scenarios. As a result, future work should utilize different methods to investigate the relationship between eccentricity and velocity perception in VR. Furthermore, the results indicate that the model may require additional parameters to describe more complex scenes, such as the spatial frequency of the stimulus or the effects of depth perception. We hope to further explore these ideas in future research to enhance the model.

8 CONCLUSION

Using a comprehensive perceptual experiment, we provided detailed measurements of the relationship between the eccentricity of a stimulus and the perceived velocity. From the results we found the temporal frequency of the stimulus to be another factor influencing this correlation. By combining these findings, we proposed an empirical model to describe this relationship. Using a secondary experiment we confirmed this model to hold for both fixation and smooth pursuit gaze types. Our VR pilot study suggests that this effect exists in more complex scenarios as well, and highlights further opportunities to fine-tune the model.

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