Why Slow Feels Fast and Fast Feels Slow: Evaluating and Predicting Speed Misperception

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Figure 1: *Speed Misperception in Visual Content. In this driving application study (detailed in Section 4), user moves at the* ***exact same speed*** *on two visually different VR scenes. However, the players perceive the motion differently. In scene 1, we removed the high-frequency objects, such as the zebra crossing and street clutter. The* ***low spatial frequency*** *background creates a compelling illusion of* ***slower*** *motion. Conversely, scene 2 with* ***high spatial frequency*** *cues makes the same speed feel noticeably* ***faster****. This marked distinction highlights how visual properties can dramatically distort perceived speed, underscoring the need for perceptually aware design in graphics and virtual reality.*

Abstract

Human perception of speed is largely driven by visual cues. However, our subjective estimations of speed are influenced by several factors that can lead to deceptive cues and speed misperception. While some prior studies have explored individual effects on speed perception, such as contrast, spatial frequency, and temporal frequency, their combined influence remains underexamined, particularly in immersive VR environments. In this work, we systematically investigate the influence and interplay of four visual factors—contrast, spatial frequency, temporal frequency, and eccentricity—on human perception of speed. To this end, *we conduct a psychophysical study* measuring subjective speed judgments across controlled stimuli and reveal significant perceptual biases induced by these factors. Based on our collected data, we learn a model to *predict the underestimation or overestimation of perceived speed* from visual scene properties. We apply and validate our findings in three immersive environments and demonstrate their influence on common VR scenarios. Finally, we discuss how understanding the factors that shape speed perception can drive the design of perceptually aligned virtual environments, with potential future applications such as correcting speed misperception and conceivably mitigating visual-vestibular conflicts by modulating perceived speed.

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1 Introduction

Whether actively moving by walking or passively being driven by the virtual scene, humans rely on an interplay of different senses to judge their speed of motion in virtual reality (VR) [28]. The visual system plays a dominant role in this, often dominating other senses, due to its ability to provide rich information about the surrounding environment [4, 42]. However, our visual system can sometimes misjudge motion, resulting in *speed misperception*—where even two objects at the same speed may appear to be moving at different speeds. For instance, driving through a tunnel can make the car feel as if it is moving faster than it actually is, due to the proximity of the walls and the rapid flow of visual cues, whereas driving in an open landscape at the same speed may feel slower [23]. Similarly, fast-moving vehicles in the far periphery might be perceived as moving more slowly than they actually are, potentially leading to misjudgments of speed [37]. Understanding and leveraging speed (mis)perception aids designing computer graphics applications and immersive environments, as it directly influences the creation of more engaging and effective virtual experiences that align with human visual perception. Therefore, in this paper, we aim to understand "when do humans misperceive speed in *visual content*?"

Previous research has extensively studied the implications of speed perception, with a significant body of work focused on vection and its role in contributing to cybersickness in immersive virtual reality systems [8, 5]. Vection is the visually induced illusion of self-motion, where the temporal displacement of scene content on the retina causes individuals to feel as if they are physically moving despite remaining stationary [12]. This phenomenon is particularly common in virtual reality (VR) environments that feature controller-operated camera movements. Specifically, studies have attributed vection to the effects of object motion [25], spatial [29], and temporal frequency changes [37] in the peripheral vision, as well as the influence of different eye movement types [14]. However, vection is predominantly caused by *unconscious perception* of moving scene background [14], while *conscious speed perception* of dynamic agents in the scene remains under investigated.

Previous works that explore general speed perception have shown that the perceived speed of moving parallel gratings is dependent on contrast levels [39, 38], suggesting that lower contrast often leads to the underestimation of speed. More recent studies have demonstrated that spatial frequency—the level of detail or texture in a visual stimulus—can significantly influence speed perception, particularly in the periphery of vision [28]. However, the majority of these studies examine the contributing factors in isolation and primarily within simplified 2D environments, leaving substantial gaps in understanding how these variables interact in more complex, immersive 3D environments. To the best of our knowledge, the combined influence of key scene parameters—including contrast, spatial frequency, temporal frequency, and object eccentricity—has not been explored.

In this work, we aim to bridge this gap by systematically investigating the subjective perception of speed in dynamic virtual environments. To this end, we first measure and analyze the speed perception of screen-displayed object motion across various dimensions through a large-scale psychophysical study. Our results and statistical analysis reveal that multiple factors in visual content significantly influence speed perception. We validate our findings in generalizable scenarios via an application study in VR, featuring three naturalistic scenes. Additionally, building on these findings, we regress a four-dimensional perceptual model that predicts speed misperception—underestimation or overestimation—based on visual content, leveraging our collected data on perceived speed. Finally, we discuss how our function can be utilized in potential applications, including designing visual content that mitigates speed misperception. This paper focuses on visually induced speed perception in "seated VR" settings, where natural self-motion cues are absent. We envision this research contributing to a more comprehensive understanding and application of human speed perception in the VR community, similar to prior work on contrast sensitivity, which has shaped perceptual graphics.

2 Related Work

When humans observe their surroundings with their eyes, they can identify temporal displacements of objects on the retina as object motion. In contrast, the movement of what we recognize as the scene background is interpreted as self-motion. While the vestibular system in our inner ear can detect linear and rotational accelerations, visual information is often the dominant sense in conflicting scenarios [4]. This bias can lead to situations where self-motion is perceived while the body is actually at rest. The effect of perceived self-motion from visual cues is known as vection [12]. While both vection and general motion perception rely on visual motion cues, they differ in interpretation and neural processing. Motion perception involves detecting and tracking movement for object recognition and interaction, discussed in Section 2.1. Vection, however, refers to the sensation of self-motion induced by large-field motion, commonly explored in VR, as covered in Section 2.2.

2.1 General Speed Perception

The perception of speed in the human visual system is influenced by multiple factors, including stimulus eccentricity, temporal frequency, contrast, and luminance. Research has shown that motion processing varies across the visual field, with peripheral vision playing a crucial role due to its faster temporal processing [26].

Studies by Stone [39] explore the perceived speed of moving parallel gratings, discovering slower perceived speed for lower-contrast gratings. They reported that the perceived speed is a quasi-linear function of the log contrast ratio. The effect of contrast in speed perception is also validated by Thompson [41]. Diener [10] experimented with the effect of spatial frequency of horizontally moving stripe patterns. They found the perceived velocity increased linearly with spatial frequency. McManus [25] investigated the role of optic flow in the far peripheral field by examining object motion effects at different eccentricities. The results showed that the most accurate judgments occurred when only the far periphery was visible, highlighting the importance of peripheral optic flow in speed perception. The recent work of Scholz [37] explores the influence of temporal frequency and eccentricity on speed perception. Their findings indicate that perceived velocity is systematically distorted depending on stimulus speed and eccentricity: slow-moving targets tend to be overestimated, while fast targets with high temporal frequency are underestimated. These distortions become more pronounced with increasing eccentricity. Hassan [18] examined the role of luminance in speed perception to demonstrate that perceived object speed is modulated by the brightness of observed patterns. Their results indicate that objects generally appear slower when luminance is reduced, even when contrast differences are accounted for.

These findings collectively highlight that speed perception is subject to variations in visual characteristics. Understanding these biases is crucial for developing applications involving motion simulation, virtual environments, and perceptually optimized display technologies. However, existing research on speed perception has largely focused on isolated factors rather than their combined influence. Furthermore, most studies have been conducted in traditional 2D viewing conditions, but not immersive 3D environments that offer enhanced visual cue from stereopsis. We address these challenges by systematically investigating the combined effects of contrast, spatial frequency, temporal frequency, and eccentricity on speed perception in stereoscopic modalities.

2.2 Speed Perception of Self-Motion

When observing dynamic content on display without physical movement, we perceive self-motion speed from the retinal optical flow, a phenomenon known as vection. In VR, the perceived speed of vection shapes our sense of movement and can even lead to cybersickness and spatial disorientation due to conflicts between visual and vestibular inputs.

Early studies by Brandt and Berthoz [8, 5] demonstrated the dominant role of peripheral vision in vection. While exposing participants to real-world rotating and linearly moving stimuli, occluding the central vision resulted in a significantly stronger perception of self-motion than covering the periphery. Palmisano [29] found that low spatial frequencies enhance vection in the periphery, while high frequencies are more effective in the fovea, reinforcing regional differences in motion processing. Previous research has demonstrated that increasing luminance contrast can enhance the sensation of vection [36, 31, 17]. Additionally, eye movement behavior influences the eccentricity dependence of vection [14, 30, 40]. Studies have shown that when a permanent fixation target is present, vection is perceived equally from both foveal and peripheral vision. However, under natural viewing conditions, where the gaze shifts dynamically across the scene, peripheral vision dominates vection perception. The interaction between spatial frequency, stimulus eccentricity, and eye movement has practical implications, particularly in the context of cybersickness in VR. Cybersickness, characterized by symptoms such as nausea, disorientation, and oculomotor strain, arises from visual-vestibular conflicts and remains a major challenge for VR adoption in the general public. Building on these findings, various techniques to mitigate vection in VR — and consequently cybersickness — often involve modifying the peripheral regions of the display. Some methods reduce motion cues by full peripheral occlusions [1, 15], while others employ more subtle peripheral blurring to dampen optic flow in the outer vision [16, 22]. Besides, Kim investigates the use of reverse optical flow to reduce VR sickness [21]. Groth [14] introduces subtle screen-space deformations that selectively alter peripheral motion flow to effectively reduce vection without disrupting conscious motion perception. These techniques underscore the critical need to understand vection mechanisms for optimizing VR experiences with minimal user discomfort.

However, most prior studies examine vection in isolation, often focusing on its link to cybersickness rather than the specific role in speed perception. Additionally, prior work often simply applies uniform motion stimuli and generalized visual degradation to address cybersickness, thereby neglecting the interaction between perceived speed and visible clarity. In this work, we systematically evaluate the visual factors influencing speed perception and explore vection within this context. These findings provide a foundation for potential applications, including designing visual environments that reduce visual-vestibular conflict for potential cybersickness mitigation, as detailed in Section 5.3.

3 Perceptual Experiment

We aim to investigate human speed perception across multiple dimensions, including contrast, spatial frequency, temporal frequency, and eccentricity. In this section, we provide a detailed description of our experiment covering the setup, participants, stimuli, and experiment protocol, followed by results and discussion.

3.1 Experimental Setup

Setup and Participants We conducted the study using a Meta Quest Pro VR head-mounted display (HMD) with a built-in eye tracker (Table 1) for presenting stimuli. Participants viewed the stimuli and interacted with the study interface via a keyboard (Figure 2b). Both the HMD and keyboard inputs were integrated and programmatically controlled using Unity. We recruited a total of 11 participants (7 male, 4 female), aged 18-27, all with normal or corrected-to-normal vision. The study protocol was reviewed and approved by our Institutional Review Board.

Specification	Details
Resolution	1800 × 1920 per eye
Refresh Rate	90Hz
Visible Field Of View	106°(horizontal)/95.57°(diagonal)
Eye Tracking Sample Rate	90Hz

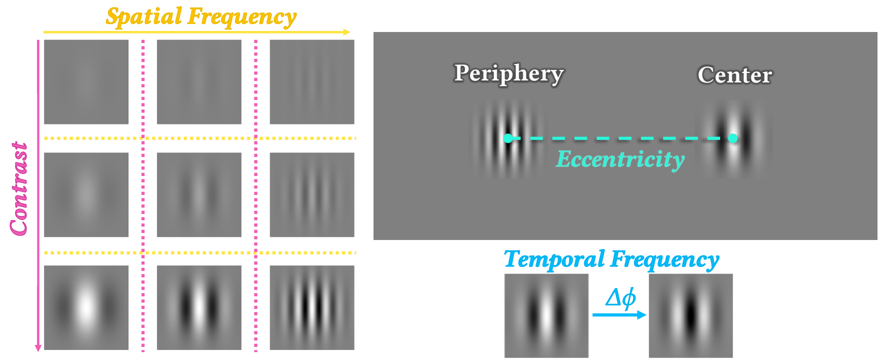
Table 1: Meta Quest Pro

Tasks and Stimuli We selected Gabor patches as visual stimuli because their sinusoidal grating structure closely approximates the receptive fields of neurons in the visual cortex — a property that has led to their extensive use in perceptual graphics and VR research [32]. The stimuli consisted of two drifting Gabor patches: one positioned centrally on the display, and the other presented at a predefined eccentricity, similar to previous work [37]. Two Gabor Patches were set at the same size (3 degrees) and the same orientation (vertically) as shown in Figure 2a. The side of *peripheral Gabor* (left or right) was randomized and counterbalanced across the trials of the study. We measured the participants' speed perception of *peripheral Gabor* through the method of adjustment.

At the beginning of each trial, both Gabor patches were simultaneously presented with two drifting speeds; the speed for the *peripheral Gabor* was set at a specified value across conditions, and the speed of *center Gabor* was a scaled version of the *peripheral Gabor* speed, with the scale factor randomly picked from the range $[0.5, 1.5]$. Participants modulated the speed of *center Gabor* to match with the speed of *peripheral Gabor* via keyboard (up arrow for acceleration and down arrow for deceleration). Participants' gaze movement during the trial was monitored by the native Meta Quest Pro eye tracker, ensuring that their gaze was always at the *center Gabor*. If the eye tracker detected that the participant's gaze shifted away from the center, the trial was automatically rejected by the program and repeated to ensure data consistency.

Conditions We studied four dimensions for characterizing the perceived speed of visual stimulus (*peripheral Gabor*): contrast ($c = \{0.0625, 0.25, 1\}$), influencing stimulus visibility and perceived intensity; spatial frequency ($f_s = \{0.5, 1, 2\}$cpd), determining the granularity of stimulus patterns; temporal frequency ($\{f_t = 2, 6\}Hz$), reflecting the speed of pattern modulation over time; and eccentricity ($e = \{10°, 20°\}$), defining the stimulus' angular distance from the foveal (central) vision. We selected the parameter ranges based on a preliminary study to balance weak and strong motion cues, while avoiding values that were either imperceptible or hypersensitive. For contrast, we chose a value slightly above the threshold $c = 0.0625$ as well as $c = 0.25$ and $c = 1$ clearly suprathreshold levels [34]. Notably, at such suprathreshold values, contrast sensitivity becomes less dependent on the spatial frequency of gratings [7, 13]. We opted for relatively low spatial and temporal frequencies, motivated by the reduced ability to perceive higher frequencies at eccentricities of 10° and 20° that we consider as practically relevant VR applications [3]. Additionally, the combination of low spatial frequencies with temporal frequencies of 2 and 6 Hz enhances the visibility of these patterns compared to their static counterparts, as supported by spatio-temporal contrast sensitivity function research [20, 9]. While the sensitivity is higher for static gratings of 2 cpd than 1 cpd [34], this is not the case for dynamic gratings and higher eccentricities that we here consider [24]. Based on preliminary testing, we excluded the conditions involving 2 cpd gratings of low-contrast at the highest eccentricity ($c = 0.0625, f_s = 2\,\text{cpd}, f_t = 2Hz, e = 20°$) and ($c = 0.0625, f_s = 2\,\text{cpd}, f_t = 6Hz, e = 20°$) as they were difficult to perceive. We varied the features of *peripheral Gabor* across the studied dimensions. The features of *center Gabor* were fixed by adopting highly sensitive parameters ($c = 1, f_s = 1, e = 0$) across all the trials. The initial temporal frequency of *center Gabor* was randomized based on the *peripheral Gabor* for the participant to perform the adjustment task. In total, we included 34 conditions (3 contrast levels × 3 spatial frequencies × 2 temporal frequencies × 2 eccentricities − 2 excluded conditions) with 4× repeats per condition, resulting in 136 trials conducted per participant. The order of conditions in experiments was randomized and counterbalanced across participants.

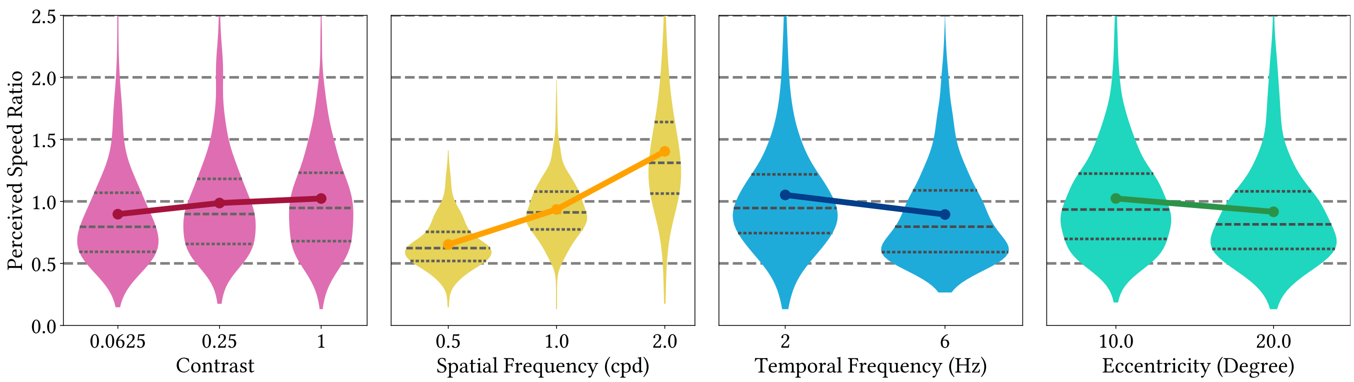
Procedure Our study followed the method of adjustment protocol, where participants adjusted the speed of *center Gabor* to match the speed of *peripheral Gabor* to the best of their perception. We also considered the staircase procedure with 2IFC (two-interval-forced-choice) task. But, since our study includes 4 dimensions and reaches 34 conditions in total, the staircase would significantly prolong the experiments and increase user fatigue. Conservatively estimating that each condition would require approximately 100 staircase trials to reliably determine perceptual thresholds, the total number of trials would have reached roughly 3,400 (34 × 100). Therefore, we measured the perceived speed by an adjustment task



(a) Stimuli and Protocal

(b) Experiment Setup

Figure 2: *Perceptual Experiment.* (a) illustrates the stimuli and protocol used in our psychophysical experiment detailed in Section 3. Participants were tasked with adjusting the speed of *center Gabor* until it was perceived as identical to the speed of *peripheral Gabor*. Across trials, the contrast, spatial frequency, temporal frequency, and the eccentricity of the *peripheral Gabor* were systematically varied as experimental parameters. The selected contrast values were $c = \{0.0625, 0.25, 1\}$, while the spatial frequency values were $f_s = \{0.5, 1, 2\}$cpd. The *peripheral Gabor* drifted with temporal frequencies of $\{f_t = 2, 6\}Hz$ and was presented at eccentricities of $e = \{10^\circ, 20^\circ\}$. The *center Gabor* remained constant across all trials, with fixed parameters of $c = 1, f_s = 1$, and $e = 0$. (b) shows the hardware and experimental setup. Participants viewed the stimuli through a Meta Quest Pro VR headset and performed the adjustment task using a keyboard.



(a) Perceptual Experiments Results

Figure 3: *Perceptual Experiment Results.* The aggregated ratio of participants' perceived speed to presented speed (r, Y-axis) is visualized across contrast, spatial frequency, temporal frequency, and eccentricity (X-axis). The line charts illustrate trends in speed perception across different parameters, with the markers laying in the mean value of data collection. The violin plots shows the data distribution and variability within each parameter group, with the inner lines illustrating the median and quartile lines of the distribution. Due to the non-uniform intervals between parameter values, we repositioned the X-axis ticks for better visual clarity.

following previous work [37]. Considering the participants' varying familiarity with VR, we conducted an instructional session at the start of the study. During the session, the participants completed 15 randomly selected practice trials while receiving guidance on how to perform the task correctly. To prevent participant fatigue, the study was evenly divided into two blocks, with a 10-minute break between sessions. During the long break, participants were asked to remove their headsets and take a complete rest. Additionally, participants were instructed to close their eyes and take a short break with the headset on after completing every ten trials to prevent eye strain caused by prolonged gaze fixation. The entire study took approximately 1.5 hours for each participant.

3.2 Results and Discussions

Speed of Gabor In the experiment, we simulated motion by continuously increasing the phase of the Gabor patch, creating a drifting Gabor setup widely used in prior studies [37]. This approach generates motion without spatial displacement across the field of view, allowing us to maintain a fixed stimulus position during the trials for eccentricity conditioning. After the experiment, we post-processed the results to convert the speed from the phase shift per second ($\Delta\phi/s$) to a more general representation in spatial shift per second ($\Delta x/s$), for broader applicability of the findings.

For a Gabor patch drifting along the horizontal axis (X-axis), we can represent it as a one-dimensional function as:

$$G(x) = \exp\left(-\frac{x^2}{2\sigma^2}\right)\cos\left(2\pi f_s x + \phi\right), \tag{1}$$

where ϕ is the phase, f_s is the spatial frequency and σ determines the size of the Gabor patch. In our experiment, σ was adjusted so that the stimulus occupied exactly three degrees of visual angle. When the phase ϕ changes by an amount $\Delta\phi$, the grating pattern of the Gabor appears shifted in space by an amount Δx. Mathematically, this relationship can be expression as: $2\pi f_s(x + \Delta x) + \phi = 2\pi f_s x + (\phi + \Delta\phi)$. Therefore, the spatial shift Δx resulting from a phase shift of $\Delta\phi$ is: $\Delta x = \frac{\Delta\phi}{2\pi f_s}$. By incorporating the recorded phase change $\Delta\phi$ and the spatial frequency f_s into the above formula, we express the speed of the drifting Gabor in the spatial dimension. The speed, denoted as ω, is measured in degrees per second by calculating Δx in angular space.

Perceived speed ratio, r We investigated the ratio of perceived speed to presented speed. This perceived speed ratio can be represented as: $r = \omega_{perceived}/\omega$, where $r > 1$ indicates that the speed is overestimated, and $r < 1$ indicates that the speed is underestimated. As shown in Figure 3, we plotted the aggregated perceived speed ratio on the Y-axis across varying conditions of contrast, spatial frequency, temporal frequency, and eccentricity on the X-axis. We adopted three statistical analyses to investigate the effect of each condition. **One-way ANOVA** to determine whether each condition significantly impacts the perceived speed ratio. **Pearson Correlation Coefficient** to assess the linear correlation between each condition and speed perception. And, **Multi-Way ANOVA** to measure the interaction effects between different dimensions for investigating the combined influences.

Contrast (c) The effect of contrast on perceived speed was found to be statistically significant, as measured by a one-way ANOVA ($F(2,1493) = 9.35, p < .001$). Additionally, Pearson correlation analysis revealed a positive relationship between contrast and the perceived speed ratio ($r(1949) = 0.092, p < .001$). Increasing contrast was observed to elevate the perceived speed, consistent with findings from prior research [39, 41, 6]. However, we observed that the magnitude of this elevation varied across contrast levels: the perceived speed ratio increased significantly from 0.90 at $c = 0.0625$ to 0.99 at $c = 0.25$, but the change was less pronounced from 0.99 at $c = 0.25$ to 1.02 at $c = 1$. This suggests that the effect of contrast on speed perception is nonlinear, with the effect diminishing as contrast exceeds a certain threshold. Further analysis confirmed that the contrast effect becomes less significant at higher levels ($F(1,1054) = 1.6192, p = 0.2035$, when $c \geq 0.25$). This finding challenges the assumption that human speed perception follows a quasilinear relationship with the log contrast ratio [39]. Our results align with the findings from Stocker [38], who reported that perceived speed varies more significantly in the lower contrast range ($c = 0.05$ to $c = 0.2$) than in the higher range ($c = 0.2$ to $c = 0.8$). It confirms that the contrast has a positive, nonlinear effect on speed perception, with diminishing impact at higher levels.

Spatial Frequency (f_s) The one-way ANOVA revealed a significant effect of spatial frequency on speed perception ($F(2,1493) = 549.48, p < .001$). A high Pearson correlation coefficient ($r(1494) = 0.6503, p < .001$) further confirmed a strong statistically positive correlation between spatial frequency and the perceived speed ratio r. Notably, the effect size of spatial frequency was the largest among all the factors studied, emphasizing its crucial role in altering speed perception. We observed that the perceived speed ratio increased significantly, from 0.65 at $f_s = 0.5$ to 1.4 at $f_s = 2$, showcasing the substantial influence of spatial frequency on speed perception. These findings align with the results of Diener [10], who conducted experiments using a moving stripe pattern. Their results show spatial frequency to be independent of the relative angular width of the stripes. This highlights the generalizability and robustness of the spatial frequency effect across different motion scenarios. In summary, spatial frequency is an influential factor in altering speed perception, exhibiting a significant and strong positive effect, with the perceived speed ratio increasing notably at higher frequencies.

Temporal Frequency (f_t) A one-way ANOVA measurement revealed a significant effect of temporal frequency on speed perception ($F(1,1494) = 44.52, p < .001$), showing an opposite trend compared to contrast and spatial frequency. The perceived speed ratio decreased from 1.05 at $f_t = 2Hz$ to 0.89 at $f_t = 6Hz$, with a negative Pearson coefficient correlation ($r(1494) = -0.17, p < .001$) confirming this relationship. This trend indicates that humans tend to underestimate the speed of fast-moving objects and overestimate the speed of slow-moving objects. This result also aligns with the findings of Diener [10], who reported that the perceived velocity increased linearly with actual speed. Temporal frequency strongly affects speed perception, leading to the overestimation of slow motions and the underestimation of fast ones.

Eccentricity (e) Similarly to temporal frequency, the effect of eccentricity on speed perception is significant ($F(1,1494) = 20.28, p < .001$) and also exhibits a negative trend ($r(1494) = -0.11, p < .001$), as revealed by ANOVA and Pearson correlation, respectively. Specifically, we observed that the perceived speed ratio decreased from 1.02 at $e = 10°$ to 0.91 at $e = 20°$. These results are in agreement with the findings of Scholz [37]. In short, eccentricity reduces perceived speed, with fast stimuli appearing slower in the periphery.

Interaction effects across dimensions We measured the interactions between each of the two dimensions using two-way ANOVA. The detailed results are shown in Table 2. Notably, only two of the pairs—namely, {Contrast (c), Spatial Frequency (f_s)}, and {Contrast (c), Eccentricity (e)}—exhibited significant interactions ($p < .05$). We visualized the interaction effects of these two pairs in detail in Figure 4. The statistics indicate that effects of the remaining pairs are relatively independent.

Dimension 1	Dimension 2	p-value
Contrast	Spatial Frequency	.001
Contrast	Temporal Frequency	.214
Contrast	Eccentricity	<.001
Spatial Frequency	Temporal Frequency	.513
Spatial Frequency	Eccentricity	.439
Temporal Frequency	Eccentricity	.479

Table 2: *Pairwise Interaction Effect p-values Between Dimensions* The table reports p-values from a two-way ANOVA analyzing the interaction effects between pairs of visual dimensions. Significant results ($p < .05$) indicate that the influence of one factor on perceived speed is modulated by the presence of another.

Contrast vs. Spatial Frequency For the {c, f_s} pair, the increasing contrast significantly raises the perceived speed ratio, as evidenced by a positive Pearson correlation at $f_s = 0.5$ ($r(526) = 0.1294, p = .002$) and $f_s = 1.0$ ($r(526) = 0.2161, p < .001$). Nevertheless, for high spatial frequency condition ($f_s = 2.0$), the contrast influence in speed perception becomes negligible ($r(438) = -0.0489, p = .306$), with a declining trend from 1.47 at $c = 0.0625$ to 1.37 at $c = 1$. It suggests that the impact of contrast on perceived speed is modulated by spatial frequency, being more pronounced at lower spatial frequencies and significantly diminished at higher ones.

Contrast vs. Eccentricity For the {c, e} pair, our analysis revealed that under a low-contrast condition ($c = 0.0625$), the perceived speed ratio decreased markedly by 28% from 1.00 at $e = 10$ to 0.72 at $e = 20$ with a significant Pearson correlation($r(438) = -0.3, p < .001$). However, for the relative high-contrast conditions, the eccentricity effect was diminished, showing only 2% reduction ($r(526) = -0.02, p = 0.58$) at $c = 0.25$ and 7% reduction ($r(526) = -0.08, p < .050$) at $c = 1$, respectively. These findings indicate that perceived speed is considerably more sensitive to changes in eccentricity with low-contrast visual stimuli, whereas in high-contrast visualization, the influence of

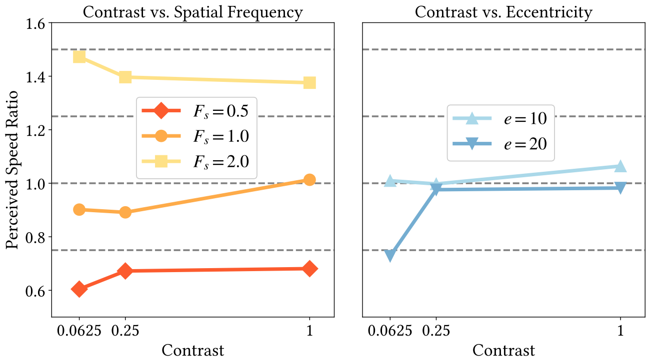


Figure 4: *Visualization of interaction effects* The sub-figures show the interaction between contrast (c) and other two factors (from left to right): spatial frequency (f_s) and eccentricity (e), the only two pairs showing the statistical significance with two-way interactions.

eccentricity on speed perception is significantly reduced.

High-order interactions In addition to examining pairwise interactions, we extended our analysis to explore higher-order interactions using three-way and four-way ANOVAs. Notably, none of the three-way interaction effects reached statistical significance ($p \gg .05$), suggesting that the combined influence of any three dimensions does not add substantial explanatory power beyond the two-way interactions. However, the four-way interaction, which simultaneously considers contrast, spatial frequency, temporal frequency, and eccentricity, was statistically significant ($p < .001$). This indicates that while individual triplet combinations may operate relatively independently, the integration of all four factors captures a unique synergistic effect on perceived speed. Such a result may reflect the holistic manner in which the visual system processes multiple cues concurrently, highlighting the importance of considering all dimensions to fully understand speed misperception. This also encourages us to build a multi-dimension function to model our speed perception, as detailed in Section 5.1.

4 Application

The results of our perceptual experiment, presented in Section 3, highlight the significant impact of four key dimensions on speed perception. While prior work has investigated the combined effects of temporal frequency and eccentricity in VR settings [37], the larger effect sizes of spatial frequency and contrast on speed perception suggest their potential importance in practical applications, yet they remain largely underexplored. To address this gap, we build on prior findings and evaluate the robustness of our speed perception results in realistic and practically applicable scenarios. Specifically, we examine whether the perceptual effects of high contrast and high spatial frequency, which are previously observed to increase perceived speed in controlled psychophysical settings, remain consistent across common VR contexts.

4.1 Experiment Setup

Stimuli For the application study, we simulated three realistic scenarios—driving, walking, and gaming—within virtual environments, as shown in Figure 5. In each scenario, participants experienced movement at a fixed speed and from a predetermined perspective. A first-person perspective was used for the driving and walking scenarios, simulating typical daily movements at two different speeds. In contrast, the gaming scenario employed a third-person, top-down perspective, where the participants experienced a runner game from an elevated viewpoint. We studied the effects of contrast and spatial frequency under two conditions. For the contrast condition (**C-C**), we implemented a camera filter to control the overall scene contrast, using the Color Grading feature of the post-process volume in the Unity game engine. For the spatial frequency condition ($\mathbf{F_s}$**-C**), spatial frequency—being an inherent property of scene content, influenced by object distribution, texture, and lighting—could not be directly and precisely controlled through post-processing filters. Therefore, we instead adjusted the spatial frequency by selectively retaining or removing high-frequency objects from the field of view.

Condition \ Scene	Driving	Gaming	Walking
$\mathbf{F_s}$**-C**	$< .001$	.005	.001
C-C	.043	.585	.016

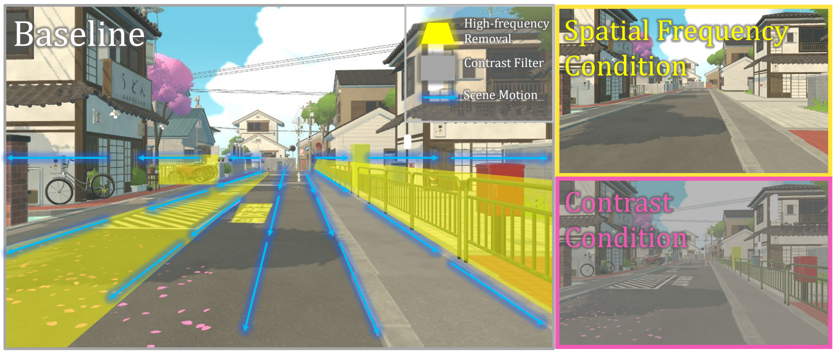
Table 3: *Evaluation in Immersive VR Scenarios.* The table presents p-values from the Binomial test with a hypothesized probability of 50% across different scenes and conditions. Significant results ($p < .05$) indicate the rejection of the random-guess null hypothesis, confirming that speed misperception is substantial.

Hardware and Participants We recruited 30 subjects (ages 18-37, 16 female, 14 male) to participate in the study. Participants remained seated and wore the Meta Quest Pro headset (detailed in Table 1) to view the scene. As eccentricity was not a factor in this experiment, participants were not required to fixate their gaze at the center, unlike in Section 3. Therefore, the participants' gaze was not monitored during this experiment, and the eye tracker remained inactive. This adjustment reduced fatigue from prolonged gaze fixation. None of the participants were aware of the research hypothesis of this study.

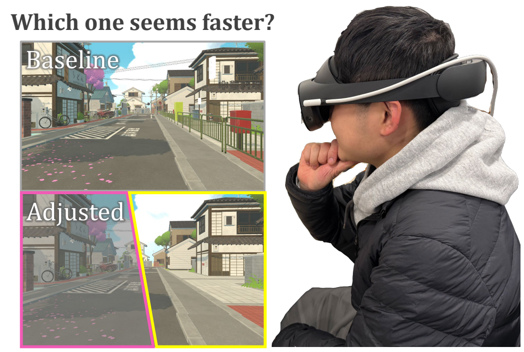
Task We conducted a two-interval forced-choice (2IFC) task, in which participants sequentially experienced two 4-second scenarios—a baseline scenario and a modified version—in each trial. Using the walking scene as an example illustrated in Figure 5a, the scenarios differed in contrast (**C-C**) or spatial frequencies ($\mathbf{F_s}$**-C**), while the speed of object movement remained constant within each trial. Specifically, in **C-C**, the modified stimuli were generated by applying a -50% contrast reduction to the baseline scenario. In $\mathbf{F_s}$**-C**, the modified stimuli were generated by removing high spatial frequency objects from the baseline scene. The Figure 5c shows the baseline, **C-C** and $\mathbf{F_s}$**-C** scenarios in the gaming scene and driving scene. Participants were tasked with identifying which of the two presented scenarios appeared faster, after observing both. They were allowed to repeat the trial if they were unsure about their response on which one seemed faster. The order of conditions were randomised across participants. A short debriefing session was conducted after the participants completed the study where they were informed that the motion speed in both scenarios was identical.

4.2 Results

As described in Section 4.1, the participants were tasked with selecting the scenario with perceptually faster motion, between the presented baseline and modified (low-contrast in **C-C** condition or low-frequency in $\mathbf{F_s}$**-C** condition) stimuli. The selection of the baseline reflects participants' perception that the motion in the modified scene appears comparatively slower, and vice versa. We calculated the percentage of participants who selected the baseline for each scene, and Figure 6 shows the aggregated 2IFC results for all 30 participants. In the **C-C** condition, the percentage of choosing the baseline was 70.00% for the driving scene, 56.67% for the gaming scene, and 73.33% for the walking scene. For the $\mathbf{F_s}$**-C** condition, the result was 90.00% for the driving scene, 76.67% for the gaming scene, and 80.00% for the walking scene. We performed a



(a) Stimuli



(b) Task

(c) Stimuli in Gaming and Driving Application Study

Figure 5: *Stimuli and Protocol of Application Study.* (a) shows the stimuli used in our application study, exemplified by the walking scene. Each trial presented participants with a baseline scenario and an adjusted scenario, where high-frequency objects were removed ($\mathbf{F_s}$**-C**) or contrast was reduced (**C-C**). (b) illustrates the study protocol. Participants identified which scenario was perceived as faster (i.e., baseline or adjusted). (c) presents a snapshot of stimuli for the baseline and adjusted scenarios for study conditions $\mathbf{F_s}$**-C** and **C-C** (from left to right), showcasing the driving and gaming scene (from top to bottom).

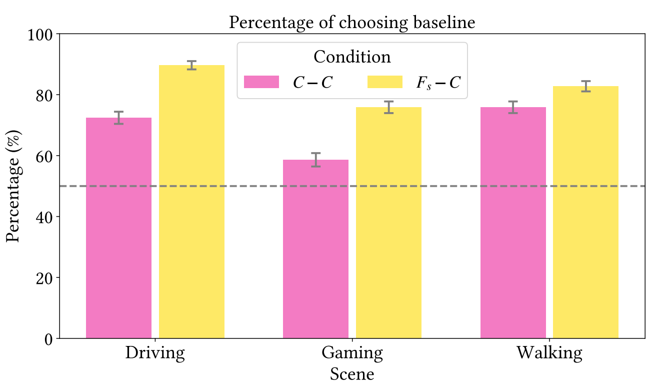
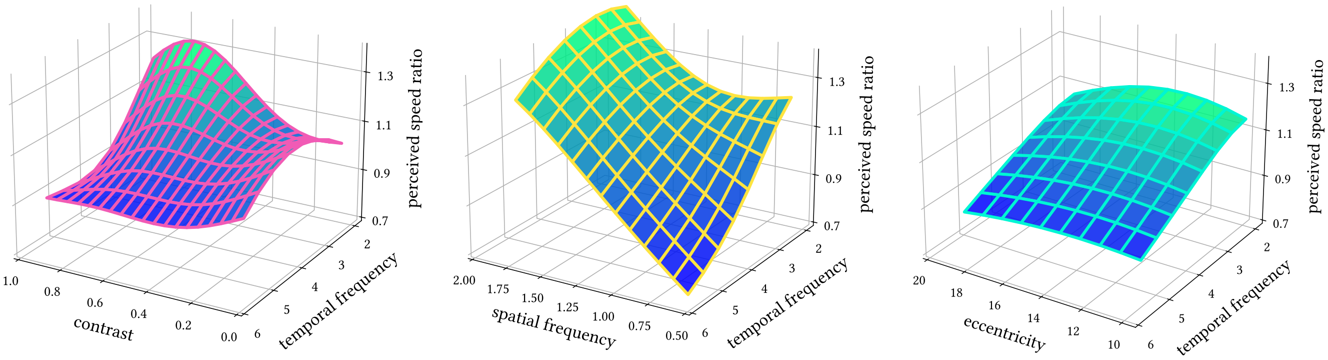


Figure 6: *Application Study Results.* The plot shows the aggregated results of 30 participants. Error bar represents standard error of measurement. The dashed line at 50% marks the chance level at which both scenarios are perceived as equally fast. A high percentage of baseline selections suggests that the adjusted scenario's speed was underestimated, showing that speed misperception can be influenced by varying scene features.

binomial test with a hypothesized probability of 50% for each condition and scene. The results are summarized in Table 3. For the $\mathbf{F_s}$**-C** condition, consistently low p-values ($p \ll .05$) across all scenes confirm that the random guess null hypothesis is rejected. The consistently high percentage of baseline selections ($\gg 70\%$) indicates that *low-frequency stimulus are perceived as slower across* all of the scenes. In the **C-C** condition, participants also perceived low-contrast stimuli as slower, with baseline selection percentages $\gg 50\%$ across scenes. The binomial test did not show significance only in the gaming scene ($p = .0585$).

4.3 Findings and Analysis

The statistical analysis indicates that participants *consistently misperceived the speed as slower in low-frequency and low-contrast scenes*. This misperception was more pronounced in the $\mathbf{F_s}$**-C** condition compared to **C-C** condition, where the effect was less notable. These findings align with our observations in Section 3, further supporting the conclusion that *spatial frequency has a stronger influence on human speed perception*. During the debriefing session, participants were informed that the motion speeds in both scenarios of each trial were identical. Surprisingly, only 6 out of 30 participants (20%) noticed this fact, providing further validation for the presence of speed misperception induced by the visual stimuli. In summary, our experiment confirms that visual content significantly influences perceived speed, demonstrating its applicability



(a) contrast - temporal frequency (b) spatial frequency - temporal frequency (c) eccentricity - temporal frequency

Figure 7: *Visualization of Predictive Speed Misperception Model.* The figure presents 3D visualizations of slices from our 4-dimensional model, depicting predictions for the perceived speed ratio $r(c, f_s, f_t, e)$. The sub-figures show the interactions between temporal frequency (f_t) and three other factors (from left to right): contrast (c), spatial frequency (f_s), and eccentricity (e).

and generalizability to immersive VR environments. The results showcased practical implications in aiding virtual environment design with appropriate speed perception as detailed in Section 5.

5 Discussion and Potential Applications

In this section, we discuss how the findings from our experimental study relate to practical applications. Specifically, we develop a four dimensional function to predict speed misperception—whether speed is overestimated or underestimated—and use to derive guidelines for immersive scene design. Additionally, we discuss potential future applications of our insights and the predictive model across immersive visual experiences.

5.1 Predicting Speed Misperception

Humans cannot perceive absolute speed; our perception is always relative to surrounding objects or reference points [41, 19]. In Section 3, we observed that all four factors (contrast, spatial frequency, temporal frequency, eccentricity) significantly influence speed perception, as confirmed by statistical validation. Although speed perception is inherently subjective and absolute speed cannot be directly estimated, these findings motivated us to develop a four-dimensional function to model the perceived speed ratio r. We chose the Radial Basis Function Neural Network (RBFNN) for its ability to model multi-dimensional relationships while ensuring local smoothness. RBFNN is widely used in perceptual VR/AR research [32, 11] due to its effectiveness in capturing human perception trends. This ratio $r := r(c, f_s, f_t, e)$ allows us to determine whether the speed is under- or overestimated in a binary sense, offering a practical framework for analyzing speed misperception.

Modeling the perceived speed ratio r To model the combined effects across four dimensions while ensuring local smoothness, we adopted a Radial Basis Function Neural Network (RBF-NN) to fit our collected perceived speed data. Specifically, we modeled the function as: $r(c, f_s, f_t, e) = \sum_{i=1}^{n} \lambda_i \rho \left(\left\| \begin{bmatrix} c \\ f_s \\ f_t \\ e \end{bmatrix} - b_i \right\|, \sigma_i \right)$ where ρ is the Gaussian basis function, and b_i and σ_i denote the radial basis center and Gaussian deviation for the i_{th} neuron, respectively. The function $r(\cdot)$ corresponds to the perceived ratio $(\omega_{perceived}/\omega)$, i.e. the perceived speed relative to the presented speed. We used an L_2 loss function and trained the RBF-NN with the Adam optimizer for 5000 epochs for $n = 30$. The learning rate was initially set to 0.01, with a tenfold decay applied at epoch 2500. We leveraged our experimental perceived speed data as detailed in Section 3 to train our predictive model. The final model is visualized in Figure 7, illustrating the combined effects of f_t and other factors on the perceived speed ratio r.

Cross Validation We performed cross-validation to evaluate the generalizability and robustness of our predictive model to unseen users. The dataset was split into two non-overlapping partitions for training and testing. Specifically, we enumerated all possible partitions by selecting 6 participants for training and evaluating the model on the remaining 5 participants, resulting in $\binom{11}{5} = 462$ unique partitions. To assess the model's generalizability, we used two quantitative metrics: Normalized Root-Mean-Square Error (NRMSE) and Normalized Mean Absolute Error (NMAE), both of which measure prediction error relative to the observed values. Across all 462 partitions, our model yielded an average prediction error of $8.83 \pm 2.27\%$ NMAE and $11.42 \pm 2.99\%$ NRMSE, indicating low prediction error on unseen users. These results confirm the robustness and generalizability of our model.

Model Usage Human speed perception is inherently relative rather than absolute. Our model predicts speed misperception by based on representative features from a given scenario and estimating its perceived speed ratio, r. The users will likely overestimate the motion speed if $r > 1$ and underestimate if $r < 1$. Similarly, for two scenes with the same motion speed but different visual features, comparing their respective perceived speed ratios (r_1 and r_2) can provide insights into user speed perception. Specifically, users are likely to underestimate the speed of one scene if $r_1 > r_2$, overestimate it if $r_1 < r_2$, or perceive both speeds as the same if $r_1 = r_2$.

5.2 Potential Application: Speed Perception Correction

The experimental results and statistical analyses in Section 3 highlight the significant effect of visual image features on perceived speed. This finding is further validated by the evaluation in Section 4, showing that individuals may perceive the same speed as faster or slower purely based on visual cues. This raises a critical question: how can we mitigate or correct these visually induced misperceptions to ensure consistent and reliable speed judgments across varying visual conditions, particularly in immersive graphics and VR? By inversely applying the Section 5.1, we can approximate the visual parameters that minimize the perceptual bias: $\{c, f_s, f_t, e\} \in r^{-1}(\{1\})$, where $r(c, f_s, f_t, e) = 1$ indicates that the perceived speed equals the physical speed. To visualize the set of

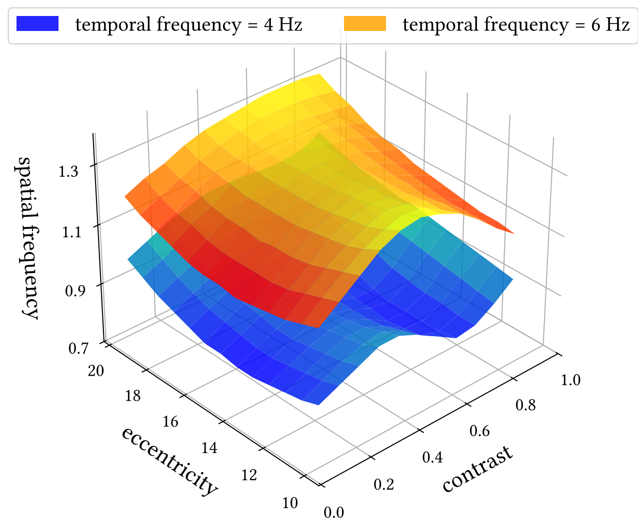


Figure 8: *Future Application in Mitigating Speed Misperception.* We visualize two 3D slices from our 4-dimensional model, showing the set of points where the perceived speed ratio, $r(c, f_s, f_t, e) = 1$. These slices represent the image features that can potentially enable correct speed perception without visual misinterpretation.

points that satisfies this condition, we project the 4D-hypersurface into two 3D-surfaces conditioned on temporal frequency, and showcase in Figure 8. These surfaces represent combinations of contrast, spatial frequency, temporal frequency, and eccentricity where the perceived and actual speeds potentially align. By analyzing the distribution of these surfaces, we can derive valuable insights for designing immersive graphics, including interactive applications and VR games, to provide corrected speed perception.

5.3 Potential Application: Visual-Vestibular Balance

Vection, the sense of self-motion induced by on-screen visual stimuli, is a primary contributor to cybersickness, particularly in VR, where it can significantly impact user experience. Prior work has explored mitigating vection by altering visual cues, such as reducing spatial frequency and contrast via image blurring [16] , limiting the field of view and hence eccentricity [2], or lowering object speed in user's vision [14]. However, these approaches often neglect the perceptual interplay between speed and visual content, leading to trade-offs such as reduced visual fidelity or diminished immersion in dynamic applications like racing games. Our proposed model can potentially address these challenges by serving as a perceptual guidance tool that accounts for the relationships between c, f_s, f_t, e. By leveraging this model, future research can explore strategies to reduce vection while preserving image quality and user immersion. For example, when incorporating the Stela contrast sensitivity function [24] into our analysis, we found that under conditions $f_t = 5$, $e = 5$, reducing the spatial frequency from $f_s = 2.6$ to $f_s = 1.3$ has minimal impact on perceptual quality—contrast sensitivity remains high at 84.3, meaning the stimulus is still perceivable when $c \geq 1/84.3$. However, our model predicts that this adjustment leads to an 8% reduction in perceived speed. Given that users are seated and thus experience zero vestibular motion, reducing the perceived speed may lessen the sensory mismatch.We believe that adapting visual parameters to modulate speed perception and subtly reduce visual-vestibular conflicts is a promising potential application.

5.4 Limitations and Future Work

Dimensions In this work, we attempt to understand the impact of contrast, spatial frequency, temporal frequency, and eccentricity on speed perception, and learn a model for the same. However, a unified model of visual speed perception could incorporate additional factors. For example, the size of the stimulus field [35] and luminance [27, 33] are shown to influence perceived speed. Studying higher-dimensional factors and capturing the full parameter space in a single experiment is challenging and time intensive. Enlarging our current work with additional dimensions could enhance our understanding of speed perception.

Relative Speed Perception In our experiment (Section 3), we employed the method of adjustment, where participants were tasked with matching the speed of the *center Gabor* to the *peripheral Gabor*. We systematically varied the visual properties of the *peripheral Gabor*, while the *center Gabor* remained constant across all conditions. Exploring variations in properties of the *center Gabor* could potentially provide deeper insights into relative speed perception between two simultaneously moving objects. However, expanding the current experiment to include diverse conditions for the *center Gabor* would be highly time-intensive. A promising direction for future research is to conduct multiple smaller-scale experiments, collectively building a generalizable dataset to comprehensively investigate relative speed misperception.

Fovea/Periphery Configuration We conducted our perceptual study using a fovea Gabor patch as a reference to measure the perceived speed of a peripheral (test) Gabor patch. The fovea/periphery configuration allows precise spatial modulation to study multiple parameters, especially for the eccentricity effects in speed matching, as used in prior research [37]. However, this fovea/periphery paradigm does not include the condition with the stimuli coming from the same region of the visual field (both in the fovea or both in the periphery). A possible approach to resolving this issue is to leverage the staircase procedure with a 2IFC (two-interval-forced-choice) task. But, as detailed in Section 3.1, this significantly expands the experiments. Extending our work beyond the fovea/periphery paradigm could provide a more thorough investigation of speed perception.

Human-in-the-loop Application While our study reveals how multiple visual parameters jointly influences speed perception, these insights can be extended to more generalizable human-in-the-loop scenarios, such as evaluating interactive task performance or enhancing navigation guidance. Applying our findings to real-world VR applications presents an exciting future direction.

6 Conclusion

In this work, we conducted a large-scale psychophysical study to systematically investigate the factors contributing to speed misperception in dynamic virtual environments. Our experimental results demonstrate that contrast, spatial frequency, temporal frequency, and object eccentricity, each significantly influence perceived speed. We also validated that our findings extend beyond controlled experimental settings, demonstrating their applicability in more naturalistic and immersive VR scenes. Building on these insights, we developed a four-dimensional function capable of predicting speed misperception under various stimulus conditions. We discussed potential future applications for this function, highlighting its utility as a perceptual guidance tool for designing visual content with corrected speed perception, and optimizing scene parameters to mitigate visual-vestibular conflicts during perceived speed modulation. Through this work, we take a step forward in bridging speed perception theory with practical applications in VR immersive technologies.

Acknowledgments

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