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Effects of Object Density on Speed Perception of First-Person Perspective Navigation Videos

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Abstract: The perception of moving speed in navigation video images differs from that in real-world environments due to the reduced availability of sensory cues. Previous studies have indicated that speed perception in first-person perspective videos is more linear in spaces filled with objects than in sparse environments. However, the impact of object density on the linearity of speed perception remains unclear. This study investigates the effect of object density on the perception of moving speed in first-person perspective videos. A user study involving 44 participants was conducted, where they viewed a movie navigating through a hallway, and their speed perception was assessed across six levels of object density using the psychophysical method of magnitude estimation. An analysis based on Stevens' power law revealed a positive correlation between the object density and perceived speed. In particular, the perceived speeds increased with the object density up to a moderate density level. The highest linearity of speed perception was observed at moderate densities. In contrast, overly dense environments exhibited diminished linearity, similar to conditions with sparse or no objects. These findings suggest the existence of a critical density threshold for maintaining linear speed perception in moving images, providing insights for the design of videos, such as navigation information.

Keywords: speed perception; first-person perspective; spatiotemporal information; linearity

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1. Introduction

The perception of moving speed in the longitudinal direction in navigation videos or virtual environments is different from that in the real world [1–9]. For instance, to perceive the same speed in virtual space as that in the real world, a human's walking speed must be 1.5 to 2.5 times faster than that in the real environment [1]. In driving simulators, drivers often underestimate their speed [4,6,10], whereas such underestimation also occurs in real environments [6]. Nonetheless, depending on the conditions, perceived velocities can exceed the nominal velocities in videos [4,11,12]. Thus, speed perception is influenced by certain conditions in movies, such as the spatiotemporal frequencies [11,13] and clarity or blurriness [2,10,14,15]. For navigation videos and virtual reality environments, where speed perception impacts the experience, inaccurate perceptual information can fail to deliver the intended experience. For this reason, numerous studies have been conducted on the factors affecting the perception of speed in virtual spaces or navigation images.

Some studies have focused on the effects of the image size or viewing angle on the speed evaluation. Wu et al. [4] conducted a psychophysical evaluation of driving speed using actual driving videos at varying image sizes during playback, revealing that the driving speed was underestimated as the image size increased. This finding appears to contradict Nilsson et al. [1], who observed that larger perspective dimensions enhanced speed perception. Hussain et al. [16] examined the impact of the viewing angle on speed perception using a driving simulator, finding that drivers estimated their speed more accurately at a 135-degree viewing angle and significantly underestimated their speed at a 60-degree angle. These studies underscore the influence of visual presentation methods, that is, the viewing conditions, on speed perception.

Several studies have explored how the features in video images affect human speed perception [3,11,17]. Otake et al. [3] examined how visual information, specifically the presence or absence of wall textures and objects, influences speed perception in first-person perspective conditions, finding that textured and object-filled environments lead to more linear and accurate perceptions of speed. Calvi et al. [17] determined that the type of median separation in a driving simulator does not impact driving speed. Zheng et al. [11] investigated how the spatiotemporal frequency during tunnel driving affects speed perception. They revealed that closely spaced markers (high spatiotemporal frequency) lead to speed overestimation, while widely spaced markers result in underestimation.

As mentioned earlier, it is clear that the perception of speed is influenced by the background images. This phenomenon can be attributed to the effects of the spatial frequency [18–21] and contrast [22,23] of moving images. Generally, moving objects with denser surface textures, indicating a higher spatial frequency, and higher contrast are perceived as moving more quickly. Similar perceptual effects are observed while driving cars [14,15].

However, thus far, researchers have not investigated how the spatial density of background images influences the linearity of speed perception. Earlier studies examined the linearity of speed perception for moving objects while the observer remained still [24–27]; these studies did not explore the relationship between the spatial frequencies of the moving objects and the linearity of speed perception. Humans' perceptual responses to physical stimuli are non-linear [28], and this also applies to speed perception [24–27]. Thus far, researchers have not investigated the dependence of this non-linearity on the object density level in images.

It is essential for video and VR application designers to understand how such non-linearity can be affected by background images. This research specifically investigates how the number of objects placed in an image, which determines the spatial frequency, affects the linearity of speed perception or judgment. Thus far, no similar studies have been reported.

We explored how different densities of object placement into a space, that is, a hallway here, affected the intensity and linearity of perceived velocity from a first-person perspective. Using a virtual hallway filled with everyday items as the visual stimuli, we employed the psychophysical method of magnitude estimation to assess speed perception across a broad range of speeds. This method, coupled with Stevens' power law, allowed us to examine the linearity of perceived speed in virtual environments, which offered insights into how the object density influences speed perception.

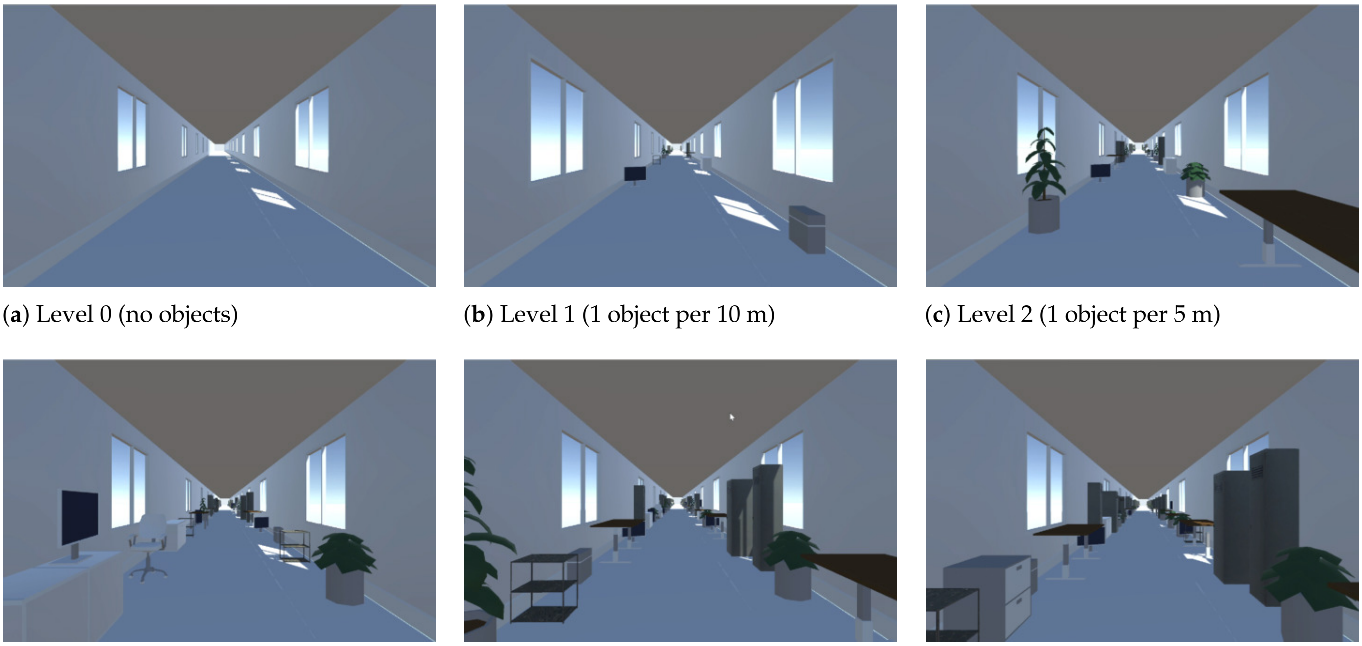
This study expands on our earlier work [29], in which we reported how the linearity of speed perception varied with the object density in a given space. Here, we provide a more detailed analysis and discussion of both the linearity and magnitude of speed perception based on the same experimental data. Since these two factors—linearity and magnitude—behave differently with changes in object density, it is essential to consider them together in the discussion.

2. The Method

2.1. Stimuli: Navigation Movies

We recorded navigation videos with software that generated a virtual space to investigate the perceived speed of spatial movement. As shown in Figure 1, we created a virtual hallway using Unity (2022.3.10f1, Unity Technologies Co., San Francisco, CA, USA), featuring an untextured ceiling, walls, and flooring, with dimensions of 4.0 m wide and 3.0 m high. The hallway was long enough to ensure that the avatar could not reach the end during a trial. Windows, serving as minimal speed cues, were placed on the walls and spaced 5.3 m apart. The windows were 1.6 m in height and 2 m in width and placed on the left and right sides of the hallway.

Objects such as tables, table lamps, chairs, lockers, plants, cabinets, monitors, and computers were randomly arranged between these windows to simulate different object densities. Six density levels were established, ranging from empty (level 0) to increasingly crowded spaces, with the distances between objects decreasing as the level increased. Level zero was a hallway with no objects. The average distances between two neighboring objects were 10 m, 5 m, 2.7 m, 1.3 m, and 0.83 m for levels 1–5, with a geometric factor of approximately 0.5. At the highest density, the object interval was nearly the smallest for the randomly appearing objects to be fit into. Similar environments were used by Otake et al. [3]; however, they used a fixed density level.



(**a**) Level 0 (no objects)
(**b**) Level 1 (1 object per 10 m)
(**c**) Level 2 (1 object per 5 m)
(**d**) Level 3 (1 object per 2.7 m)
(**e**) Level 4 (1 object per 1.3 m)
(**f**) Level 5 (1 object per 0.83 m)

Figure 1. First-person view of the starting point of the virtual hallway. From (**a**–**f**), the hallway at object density level 0 (no objects), 1 (1 object per 10 m), 2 (1 object per 5 m), 3 (1 object per 2.7 m), 4 (1 object per 1.3 m), and 5 (1 object per 0.83 m), respectively. Levels 0 and 3 were adapted from [29].

In the virtual hallway, a camera set 1.6 meters from the ground moved straight ahead. The scenes were provided to the experimental participants from a first-person perspective. The camera's speed was set at six levels, with jogging speed as the maximum, 0.91 m/s, 1.22 m/s, 1.60 m/s, 2.11 m/s, 2.78 m/s, and 3.68 m/s, following a geometric ratio of 1.32. To determine this ratio, the authors and two colleagues (four assessors in total) conducted the 1-up-3-down method [30], investigating the velocity distinguishable from 1.60 m/s. This method enables the determination of the 79.4% discrimination threshold with relatively low experimental costs. Each assessor performed this procedure twice, and the mean threshold across all assessors was adopted. The resulting mean and standard deviation were 2.11 m/s and 0.18 m/s, respectively.

The participants sat 3 m away from the screen (1.4 m × 2.5 m) onto which the hallway was projected (EB-FH52, Seiko-Epson Corp., Suwa, Japan).

2.2. Participants

A total of 44 university students in their 20s (mean age: 21.3 years) participated in the experiment. All had normal or corrected-to-normal vision with an acuity of 1.0 or better. The participants were unaware of the purpose of the experiment and reported no health issues on the day of participation. A total of 19 out of 20 participants had no prior experience with similar experiments. All of the participants provided written informed consent before taking part in this study.

2.3. Procedure

Using the psychophysical magnitude estimation method, the participants compared the perceived speed of each test stimulus against a reference stimulus (1.6 m/s velocity, no objects). They reported the number of times faster the test stimulus was compared to the reference stimulus as a positive number. For example, when the locomotive speed of a test stimulus was perceived to be 1.5 times faster than that of the reference stimulus, the answer was 1.5. They evaluated 36 test stimuli across six object densities and six velocity levels. Each stimulus lasted 10 s at a constant speed, presented in random order. Every five trials, the participants returned to the reference stimulus for comparison. For every ten test stimuli, they took a one-minute break. The experiment lasted approximately 40 min.

2.4. The Ethical Statement

The protocol for this study was approved by the Institutional Review Board, Hino Campus, Tokyo Metropolitan University (H23-009).

2.5. Analysis

First, outlier detection was performed using the 1.5 times interquartile range (IQR) method, excluding outliers in the participants' estimates from further analysis. For each combination of navigation velocity and density level, we removed participants' magnitude estimates that exceeded the third quartile plus 1.5 × IQR or fell below the first quartile minus 1.5 × IQR. As a result, 115 outliers were identified out of 1584 samples (7.3%).

The perceived speeds were analyzed using Stevens' power law [28]. This links the actual intensity of a physical stimulus with its perceived intensity, noting that their relationship is non-linear. This law is useful for approximating the perceived speed in navigation videos [3,13]. The model formula is

$$v_p = k v_n^{\alpha}, \tag{1}$$

where perceived speed (v_p) is a function of nominal speed (v_n), with the constants k and α representing the relationship between v_p and v_n. The power exponent α of the function determines the linearity between the actual and perceptual quantities. When $\alpha = 1$, the perceived speed is linear. α values less than 1 make differences in higher speeds less discernible. Another constant k determines the intensity of the perceived velocity.

To determine α and k, we linearized the model (1) using natural logarithms and employed the least squares method for estimation using the regress function from MATLAB (2023b, MathWorks Inc., Natick, MA, USA):

$$\log v_p = \log k + \alpha \log v_n. \tag{2}$$

The variables were then compared across different density levels using t-tests while adjusting for multiple comparisons with Bonferroni correction of factor 15 (${}_6C_2$).

3. Results

As shown in Table 1, the values of α were 0.642, 0.738, 0.764, 0.697, 0.61, and 0.629 for the object density levels of 0 to 5, respectively. All of these values are significantly smaller than one. Figure 2 shows bar figures of the α values and the results of the statistical comparison. Significant differences were found between several pairs of object density levels: levels 0 and 2 ($t(481) = 3.25$, $p = 0.017$), levels 1 and 4 ($t(467) = 3.18$, $p = 0.022$), levels 2 and 4 ($t(481) = 4.13$, $p = 5.4 \times 10^{-4}$), and levels 2 and 5 ($t(482) = 3.62$, $p = 4.4 \times 10^{-3}$). At object density level 2, the perceived speed was closest to linearity, as the α value was nearer to 1 compared to those for the other object density conditions. The values for levels 4 and 5 were smaller than that for level 2 and close to the value for level 0, suggesting that the linearity of speed perception became low at high object density levels.

Table 1. α value (power exponent of Steven's power law model) for each object density level. The t- and p-values represent comparisons between α and one.

Object Density Level	α	s.e.	t	p
Level 0	0.642	0.026	14.0	<0.001
Level 1	0.738	0.032	8.30	<0.001
Level 2	0.764	0.027	8.62	<0.001
Level 3	0.697	0.029	10.6	<0.001
Level 4	0.610	0.025	15.5	<0.001
Level 5	0.629	0.025	14.7	<0.001

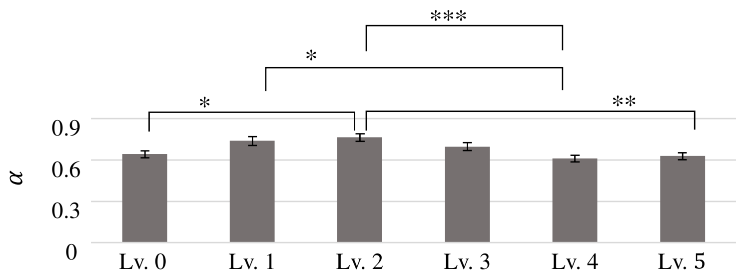


Figure 2. α values for each object density level. *, **, and *** mean a significant difference at $p < 0.05, 0.01$, and 0.001, respectively, with Bonferroni correction of factor 15.

Further, as shown in Table 2, the values of k were 0.931, 0.924, 0.982, 1.10, 1.06, and 1.13 for object density levels of 0 to 5, respectively. The values of k at levels 0 and 1 were significantly smaller than 1, and those at levels 3 to 5 were significantly greater than 1. Figure 3 shows the result of the t-tests about $\log k$, a parameter describing the magnitude of perceived speed. Significant differences were found between several pairs of object density levels: levels 0 and 3 ($t(488) = 8.91$, $p < 0.001$), levels 0 and 4 ($t(478) = 7.54$, $p < 0.001$), levels 0 and 5 ($t(479) = 10.71$, $p < 0.001$), levels 1 and 2 ($t(482) = 2.95$, $p = 0.048$), levels 1 and 3 ($t(493) = 8.42$, $p < 0.001$), levels 1 and 4 ($t(466) = 7.12$, $p < 0.001$), levels 1 and 5 ($t(468) = 9.97$, $p < 0.001$), levels 2 and 3 ($t(495) = 5.94$, $p = 4.3 \times 10^{-8}$), levels 2 and 4 ($t(481) = 4.41$, $p = 1.6 \times 10^{-4}$), levels 2 and 5 ($t(482) = 7.50$, $p < 0.001$), and levels 4 and 5 ($t(481) = 3.25$, $p = 0.017$). As a general trend, the k values increased as the density level increased.

Figure 4 presents the mean perceived velocities along with the standard errors among the participants, as well as the approximated functions of Stevens' power law for different object density levels. The coefficients of determination (R^2) were 0.726, 0.691, 0.762, 0.704, 0.711, and 0.721 for density levels 0–5, respectively. While visually assessing the linearity of these curves is challenging, the differences in the perceived magnitudes across the density levels are evident. Specifically, the magnitudes for level 0 (blue) and level 1 (gray) are relatively lower compared to those of the other curves, whereas those for level 3 (green) and level 5 (red) are noticeably higher. These vertical placements of the curves correspond to the $\log k$ values presented in Table 2 and Figure 3.

Table 2. $\log k$ values of Stevens' power law model for each object density level. The t- and p-values represent comparisons between $\log k$ and zero.

Object Density Level	$\log(k)$	s.e. of $\log(k)$	k	t	p
Level 0	−0.0721	0.0129	0.931	−5.61	<0.001
Level 1	−0.0793	0.0156	0.924	−5.08	<0.001
Level 2	−0.0183	0.0136	0.982	−1.35	0.178
Level 3	0.0982	0.0142	1.10	6.94	<0.001
Level 4	0.0628	0.0124	1.06	5.05	<0.001
Level 5	0.1200	0.0125	1.13	9.59	<0.001

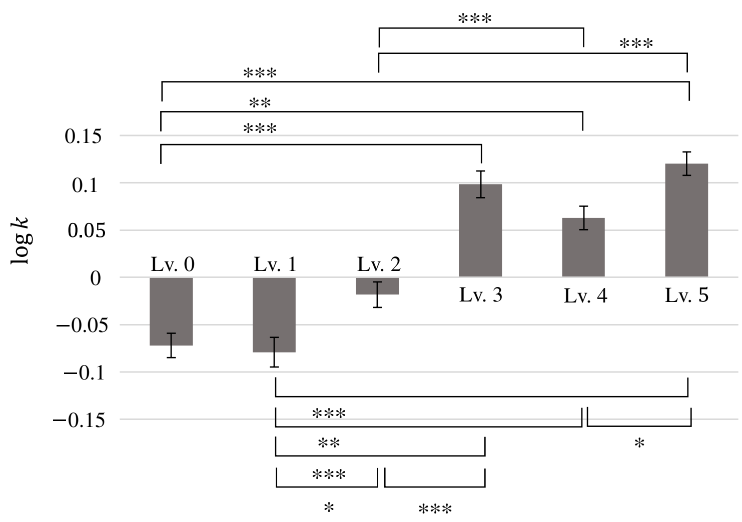


Figure 3. $\log k$ values for each object density level. *, **, and *** mean significant difference at $p < 0.05$, 0.01, and 0.001, respectively, with Bonferroni correction of factor 15.

Figure 5 shows the relationship between the perceived velocities and object density levels by distinct v_n values. Table 3 shows the Spearman's rank correlation coefficients between the perceived velocity v_p and the object density level by nominal speeds. For all velocity levels, weak or moderate and significant correlation coefficients were observed. In other words, the higher the object density, the higher the perceived speed, regardless of the nominal speeds.

From levels 0 to 3, the perceived velocity increased monotonically with the object density. After level 3, there seemed to be no substantial change in the perceived speed. To investigate this trend in a post hoc manner, we compared the perceived speeds at level 3 and those at the other levels using one-way ANOVAs with the object density level as the factor, with Bonferroni correction of factor five. Significant differences were found between object density levels 3 and 0 ($F(1, 491) = 22.5$, $p < 0.001$), levels 3 and 1 ($F(1, 499) = 29.3$, $p < 0.001$), and levels 3 and 2 ($F(1, 496) = 7.09$, $p = 0.040$). There were no significant differences between levels 3 and 4 ($F(1, 492) = 4.47$, $p = 0.175$) and levels 3 and 5 ($F(1, 493) = 1.60$, $p = 1.00$). These results suggest that as the object density increases from low to medium, the perceived speed rises monotonically; however, beyond a certain density, it plateaus.

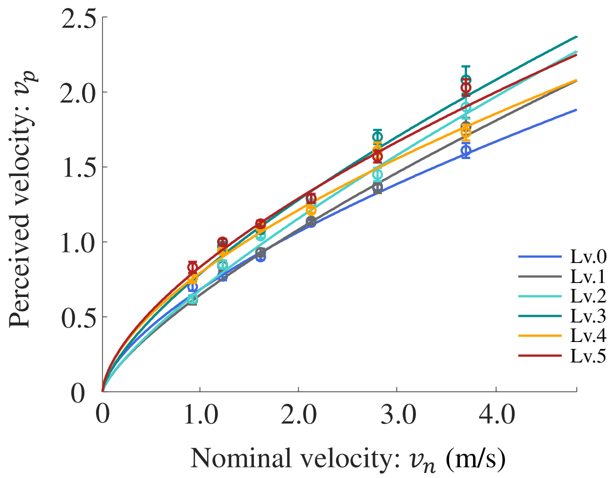


Figure 4. Means and standard errors of perceived velocities for five levels of object arrangement density.

Table 3. Spearman's rank correlation coefficient between perceived velocity v_p and object density level by nominal speeds. p- and t-values indicate the levels of significance tests.

Nominal Speed v_n (m/s)	N	Correlation Coefficient	t	p
0.91	255	0.231	3.78	$<$0.001
1.22	248	0.432	7.50	$<$0.001
1.60	250	0.528	9.79	$<$0.001
2.11	228	0.358	5.75	$<$0.001
2.78	240	0.340	5.58	$<$0.001
3.68	247	0.259	4.19	$<$0.001

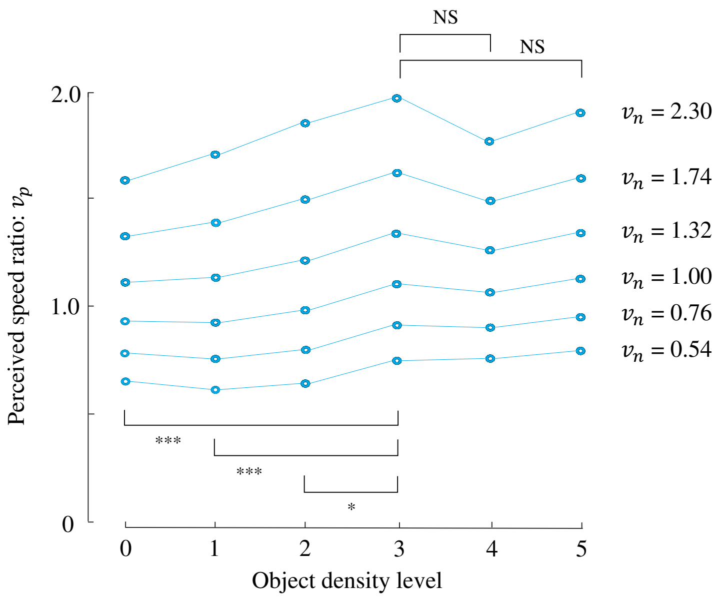


Figure 5. Mean perceived velocity as a function of object density levels. Rearrangement of Figure 4. * and *** mean significant differences from perceived speed at level 3 at $p < 0.05$ and 0.001, respectively, with Bonferroni correction of factor 5. NS indicates not significantly different.

4. Discussion

We observed that the scaling factor k, reflecting the perceptual intensity, varied within the range of 0.924–1.13 and increased with object density, peaking at the highest density level. As shown in Figure 5, in the range of object density levels 0 to 3, the higher the density, the faster the perceived speed was. There was no significant difference between level 3 and levels 4 and 5. These findings partly align with the study by Zheng et al. [11], who noted that higher spatiotemporal frequencies in the visual cues lead to speed overestimation, whereas medium and low frequencies result in underestimation when using a VR driving simulator in a tunnel. While Zheng et al. [11] employed the method of limits for their psychophysical assessment, we used the method of magnitude estimation; nevertheless, both studies observed similar perceptual effects of object density, supporting the robustness of our findings. Similarly, previous experiments with navigation video determined that spatially dense images appear to be faster [13,31]. Further, it is known that moving grating scales are perceived to be faster with an increase in the spatial density of the grating [18–20]. These insights support the notion that spatiotemporal frequencies, determined by the object density in navigation movies, significantly influence the perceived speed across various scenarios, such as walking through hallways or driving a car in tunnels with wall markers. Nonetheless, the environments tested in [11] and this study were both relatively enclosed spaces; experiments in open-air environments will be conducted in the future.

Another potential explanation for the acquired results is the perceived width of the hallway. In studies using driving simulators, it was found that drivers reduced their speed when the roadway was narrow [31–34]. Researchers have suggested that driving speed might be overestimated on narrow roads. In our conditions, the hallway might have felt narrower with an increased object density level. Thus, as the density increased, the perceived speed may have increased as well.

According to Table 1, and Figure 2, α shows an increasing trend in the range of object density levels 0–2 but a decreasing trend above level 3. α is the value indicating the linearity of speed perception; the closer $\alpha = 1$, the more linear the perceived speed. α varied in the range of 0.610–0.764, and all of the object density conditions resulted in non-linear speed perception such that the differences at greater speeds were less discernible, that is, $\alpha < 1$. The α value peaked at level 2, at which the linearity tended higher than it did at the other levels. We expected the speed perception to be more linear with increasing object density levels because more dimensional cues would be available at higher density levels. However, the linearity of speed perception decreased as the density level reached higher than 2.

Visual crowding [35–37] partially explains the results on linearity. In peripheral vision, cluttered visual information, such as letters or objects, is difficult to recognize. At levels 4 and 5, when the object density was high, the types and sizes of furniture might not have been accurately judged. As a result, at these levels, the furniture might not have functioned as dimensional information, leading to a decrease in the linearity of speed perception compared to that at level 2. This suggests that dimensional information should be arranged in space to the extent that object recognition in peripheral vision can function effectively. Thus far, no studies have investigated the linearity of speed perception with a varying object density or spatial frequency, and this study could be a first step, raising some questions to be tackled in future.

Furthermore, peculiar phenomena may have occurred only when the density was high. Zheng et al. [11] observed that object size, influencing the spatiotemporal frequency, impacts speed perception, with larger objects producing unique effects under high-frequency conditions. They found that the perceived speed monotonically increased with the object density in the space only when small or medium-sized objects were used.

When large objects were arranged in the space, a monotonic increase was not found at a high density. In our experiments, the arrangement of taller lockers in high-density settings might have distinctively influenced the speed perception compared to that in lower-density conditions. Nonetheless, as of now, the reason why the α value did not linearly vary with the object density remains unclear. Future research will explore how the object size affects the linearity of perceived speed.

The limitations of this study are outlined as follows. We used objects such as furniture, plants, and computer displays, the dimensions of which the participants could easily imagine. However, the use of these objects made it challenging to accurately compute the spatiotemporal frequencies of the visual stimuli, complicating direct comparisons with other studies, such as [11]. One possible solution would be to use a specific type of furniture arranged at regular intervals in the hallway. However, such an artificially structured environment would reduce its ecological validity. Future research should explore methods that strike an appropriate balance between experimental control and naturalistic settings.

Our analysis was based on Stevens' power law; however, it may not have fully captured the experimental data, as indicated by the R^2 values of the curve fitting (ranging from 0.691 to 0.762). The use of more accurate models could potentially refine our conclusion.

Additionally, all of the participants in this study were in their 20s, raising concerns about the generalizability of object density effects on speed perception across different age groups. For instance, older individuals tend to exhibit reduced sensitivity to changes in the speed of a moving vehicle, leading to smaller power exponents in Stevens' law models [25]. Further research is needed to explore these effects across a broader demographic range.

5. Conclusions

Few studies have explored the effect of the object density in movies on the perception of navigation speed, with the exception of [11]. This study, in particular, pioneers an examination of how object density affects the linearity of speed perception.

Perceived speed was modeled using Stevens' power law, where the power exponent α and the coefficient k represent the linearity between the nominal and perceived speed and the intensity of perceived speed, respectively. At a density level of 2 (with one object per 5 m), the linearity was yjr highest, with $\alpha = 0.764$. The linearity of speed perception peaked at moderate density levels but decreased at higher density levels. Additionally, a low to moderate correlation was found between the object density and perceived speed, with the speed being perceived as faster in denser scenes.

These findings are crucial for the design of navigation videos and virtual spaces where accurate speed perception is essential. Future research should investigate the underlying causes of these changes in the linearity of speed perception.

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Institutional Review Board Statement: This study was approved by the Institutional Review Board, Hino Campus, Tokyo Metropolitan University (R6-009), on 19 April 2024.

Informed Consent Statement: Written informed consent was obtained from all of the participants involved in this study.

Data Availability Statement: The data can be accessed by contacting the corresponding author, provided the request aligns with an accountable purpose.

Conflicts of Interest: The authors declare no conflicts of interest.

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