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Poster

Virtual Reality Space Moderately Filled with Objects for Linear Self-locomotive Speed Perception

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Abstract

This study investigates how object density in virtual reality (VR) affects self-moving speed perception. Using 44 participants, speed perception across six object density levels was assessed through magnitude estimation. The analysis based on Stevens' power law, found that the perceived speed is the highest linearity at moderate object density. Excessive or sparse object environments led to reduced linearity. The findings suggest a critical object density threshold for maintaining accurate speed perception in VR, offering insights for designing immersive environments.

CCS Concepts

• ***Human-centered computing*** $\rightarrow$ ***Virtual reality;***

1. Introduction

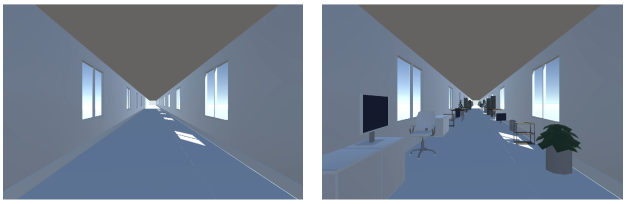
Perception of self-moving speed in virtual environments is slower than in the real world [OOA23]. Previous studies have shown that virtual environment features, particularly background images, influence speed perception. For example, denser surface textures are perceived as faster due to higher spatial frequency [ZDXC18]. This study investigates how object density in a virtual space, which influences spatial frequency, affects the linearity of self-locomotive speed perception. We examined how varying object densities impact the intensity and linearity of perceived speed from a first-person walking perspective. Using a virtual hallway with everyday objects, we applied the psychophysical method of magnitude estimation across different speeds. Combined with Stevens' power law, this approach provided insights into how object density influences speed perception in virtual environments.

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

2. Method

2.1. Stimuli: Virtual space

As shown in Fig. 1, We created a virtual hallway using Unity (Unity 2022.3.10f1, Unity Technologies Co., SF), featuring a solid but untextured ceiling, walls, and floor, with dimensions of 4.0 m wide, 3.0 m high, and long enough. Windows were placed at 5.3m intervals on either side of the corridor to provide minimal speed cues. Objects of imaginable size were placed randomly between these windows to simulate different object densities. Six density levels were used, with no objects at level 0. The distances between objects were 10 m, 5 m, 2.7 m, 1.3 m, and 0.83 m for levels 1-–5, decreasing by a geometric factor of 0.5. At the highest density (level 6), objects were placed at nearly the minimum interval possible.



(a) Level 0 (no objects) (b) Level 3 (1 object per 2.7 m)

Figure 1: First-person view of the starting point of the virtual hallway. From (a)–(d), the hallway at object density level 0 (no objects), and 3 (1 object per 2.7 m), respectively.

An avatar 1.6 meters tall moved straight ahead at constant speed. The scenes from a first-person perspective were provided to the experimental participants. Avatar speeds were set at six distinct levels, with velocities of 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 progressive ratio of 1.32.

2.2. Procedure

A total of 44 college students in their 20s (mean age 21.3 years) who were unaware of the purpose of the experiment participated in the experiment. All participants provided written informed consent before participation.

Participants sat 3 m away from the screen (1.4 m $\times$ 2.5 m), on

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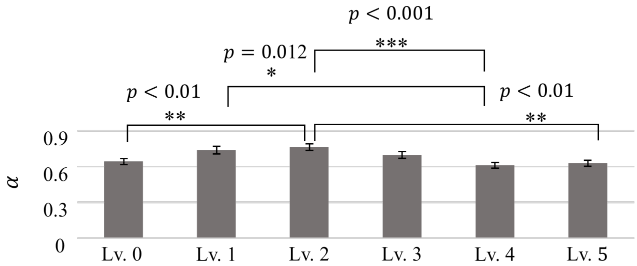

Figure 2: α values for each object density level. *, **, and *** mean significant difference at $p < 0.05$, 0.01, and 0.001, respectively, with Bonferroni correction of factor 15.

which the hallway was projected. Using the psychophysical magnitude estimation method, they 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. They evaluated 36 test stimuli across six object densities and six velocity levels. Each test stimulus lasted 10 seconds at a constant speed, presented randomly. For every five trials, participants returned to the reference stimulus for comparison. For every ten test stimuli, they took a one-minute break. The experiment lasted approximately 40 minutes.

2.3. Analysis

The perceived speeds from the experiment were analyzed using Stevens' power law [Ste57]. This links the actual intensity of a physical stimulus with its perceived intensity, noting their relationship is non-linear. 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 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. In VR, α values are typically less than 1, making differences in higher speeds less discernible. Another constant k determines the intensity of perceived velocity. Outlier detection was performed using the 1.5 times interquartile ranges, excluding outliers of v_p for further analysis. The number of outliers was 115 out of 1584 samples (7.3%).

To determine α and k, we linearized the model (1) using natural logarithms and employed the least squares method for estimation. The variables were then compared across different density levels using t-tests while adjusting for multiple comparisons with the Bonferroni correction of factor 15 (${}_6C_2$).

3. Result

The values of α were 0.642, 0.738, 0.764, 0.697, 0.61, and 0.629 for object density levels of 0 to 5, respectively. All of these values are significantly greater than zero.

Fig. 2 shows the bar figures of α values and the results of statistical comparison. Significant differences were found between several pairs of object density levels: levels 0 and 2 ($t(481) = 3.25$, $p = 0.0099$), levels 1 and 4 ($t(467) = 3.18$, $p = 0.012$), levels 2 and 4 ($t(481) = 4.13$, $p < 0.001$), and levels 2 and 5 ($t(482) = 3.62$, $p = 0.0027$). In object density level 2, the perceived speed was the most linear because α is closer to 1 than those for the other object density conditions. The values for levels 4 and 5 were smaller than those for level 2 and close to the value for level 0, suggesting that the linearity of speed perception becomes small at the high object density levels.

4. Discussion

This section discusses the relationship between object density and linearity of perceived velocity.

According to Fig. 2, α shows an increasing trend in the range of object density levels 0–2, but a decreasing trend above level 3. α varied in the range of 0.610–0.764, and the value topped at level 2. α is the value indicating the linearity of speed perception; the closer $\alpha = 1$, the more linear is the perceived speed. All the object density conditions resulted in nonlinear speed perception in a way that differences in greater speeds are less discernible. Under high-density conditions, tall lockers sometimes covered up windows that provided cues for speed estimation. Zheng et al. [ZDXC18] observed that object size, influencing spatiotemporal frequency, impacts speed perception, with larger objects under high-frequency conditions producing unique effects. In our experiments, the arrangement of taller lockers in high-density settings might have distinctively influenced speed perception compared to lower density conditions. Future research will explore how object size affects the linearity of perceived speed.

5. Conclusion

This study is the first to examine how object density affects the linearity of speed perception in VR. Speed perception was modeled using Stevens' power law, with the power exponent (α) representing linearity and the coefficient (k) indicating perceived speed intensity. The highest linearity occurred at moderate density levels (1 object per 5 m), where ($\alpha = 0.764$). While speed perception increased in denser scenes, linearity decreased at high densities. These findings are important for designing VR environments with accurate speed perception. Future research should explore how object size impacts speed perception linearity.

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