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RESEARCH ARTICLE

Perception of Self-Moving Speed in Different Visual Cue and Viewpoint Conditions in Virtual Reality Environment

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Review Board, Hino Campus, Tokyo Metropolitan University, under Approval No. H22-054.

ABSTRACT The perception of geometric cues in virtual spaces differs from that in actual spaces due to the reduced amount of information available in virtual spaces. To investigate the perception of own motion speed in virtual spaces, we conducted a user study involving 30 participants. We manipulated the amount and type of visual information and the viewpoint (i.e., first- or third-person perspective) in the virtual space, and investigated the subjective speed perception in a broad speed range using the psychophysical method of magnitude estimation. We investigated three types of virtual hallways with different scenery: the bleak hallway with little visual information, the hallway filled with objects with easily predictable dimensions, and the hallway with a textured wall that provided greater optical flows but little dimensional cues. Our results show that the speed was perceived to be slower in the bleak hallway than in the other hallways at some speed levels for both the first- and third-person perspective conditions. For the first-person perspective condition, the virtual space with the larger amount of dimensional information could lead to a more linear or accurate speed perception. In the third-person perspective condition, the speed perception was more linear than in the first-person perspective condition for the bleak and textured-wall conditions, and the differences in linearity between different hallway conditions diminished. Designers of virtual reality content need to know these properties of speed perception in virtual spaces.

INDEX TERMS Speed perception, locomotion, dimensional cue, Stevens' power law, wall texture.

I. INTRODUCTION

The perception of geometric cues, including distance and size, in virtual spaces differs from that in actual spaces due to the reduced amount of information available in virtual spaces compared to actual spaces [1], [2], [3]. One example of this is the perception of one's own locomotion speed. The perceptual cues obtained in a virtual space are less than in an actual space, resulting in a perceived speed that is considered lower in the virtual space [4], [5]. This limitation prevents the virtual space from providing the intended user experience. The speed perception of self-motion needs to be accurate, for instance, for driving simulators [6], in which drivers' behaviors closely resemble those in actual environments.

Numerous studies have investigated speed perception in virtual environments [5], [7], [8], [9], [10], [11], [12], [13]. For instance, Caramenti et al. [7] reported that a speed of 12 km/h in a virtual space was underestimated by 31%. Similarly, Nilsson et al. [5] reported that in virtual environments, humans did not perceive a walking speed similar to that in actual environments unless it was approximately 1.5–2.5 times faster than in an actual environment. Although

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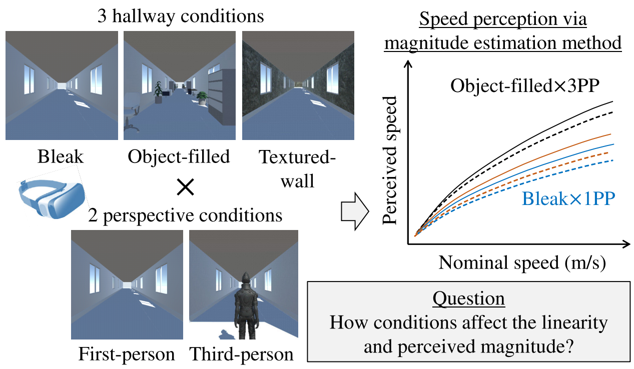

FIGURE 1. Scheme of the study. The perception of self-motion speeds are investigated via the psychophysical method of magnitude estimation under different speed, scenery, and perspective conditions. The magnitude levels and nonlinearity of the human responses are discussed.

most studies agree that self-speeds in virtual environments are perceived less than actual or nominal speeds, Perrin et al. [11] reported that such underestimation of locomotive speed in virtual environments was not observed when people matched their walking speeds on a treadmill with moving scenes viewed through a virtual reality (VR) headset. Many of these studies have compared speed perception between virtual and actual spaces [4], [5], [7], [8], [11], [14]. This is because they aimed to investigate the effect of differences in the amount of perceived information in real and virtual environments on speed perception. However, it is possible that different quality of visual information in the virtual space would result in different speed perceptions. In particular, similar to the perception of motion speed of grating scales or spatial patterns [15], [16], [17], [18], [19], it is expected that the perceived speed in virtual spaces increases with larger spatiotemporal frequency in visual stimuli or optical flows. In general, a pattern with a high spatial frequency feels faster than that with a low spatial frequency even when their speeds of rotation or translation are equal.

Several studies have investigated the impact of fogs or blurs in virtual spaces on human speed perception [12], [20], [21], [22], [23]. For instance, Garner and D'Zmura [20] demonstrated that adding fogs to a virtual space and decreasing the contrast in a scenery can impair the ability of an individual to discriminate speeds. However, there was a group of participants who were unaffected by the fog. Moreover, reports on the effects of fog on speed perception are inconsistent. The inconsistency of the results between these studies might be due to differences in the scenery behind the fog. Therefore, it is natural to investigate whether other types of visual qualities, particularly dimensional cues, are significant. When objects, of which sizes are known or easily imaginable, are seen in virtual environments, such objects can be dimensional cues to judge spatial distances in virtual spaces.

However, earlier studies have not investigated how such visual qualities in virtual environments affect the speed perception. To address this question, we conducted a study in which we compared the speed perception in three types of virtual environments: a bleak hallway with few dimensional cues, a hallway filled with objects with easily imagined dimensions, and a hallway with a textured wall providing large optical flows but little dimensional information (Fig. 1). We hypothesized that the object-filled hallway, which provides the most dimensional cues, would result in the fastest and most linear perception of motion speeds. In contrast, the bleak hallway would result in the slowest perception of motion speeds due to the limited dimensional cues. The textured-wall condition would fall between the bleak and object-filled conditions, providing a large optical flow but limited dimensional cues.

Another objective of our study is to compare speed perception between two viewpoints: first-person and third-person. Previous studies have largely investigated the perception of walking or moving speed in virtual spaces from a first-person view [5], [7], [8], [13], [24] and have yet to compare the first- and third-person view conditions regarding the perception of self-locomotive speed. However, in typical VR content, such as games and commercial metaverse services, users are allowed to switch between first- and third-person perspectives [25], [26], [27], [28]. Therefore, VR content designers need to understand how perceived speeds differ between these two viewpoints. In general, previous studies have shown that spatial recognition with the third-person perspective is nearly equal to or better than that with the first-person perspective [29], [30], [31], [32], [33]. Additionally, the visualization of the avatar in the virtual space effectively influences tasks requiring accurate spatial recognition [34]. For example, in a darts-throwing training scenario, training using a virtual environment with a first-person view was demonstrated to be less effective than that with a third-person view regarding post-training performance [33]. Therefore, it is important to investigate whether the perspective point influences the perception of self-speed, which is related to spatial recognition in the virtual space (Fig. 1).

We investigated speed perception across a broad range of speeds using the psychophysical method of magnitude estimation. Previous studies have typically employed tasks to compare and match perceived speeds between actual and virtual environments for only a single or small number of speed levels [5], [7], [8], [9], [10], [11], [12]. However, human perception is generally nonlinear [35], and speed perception may differ at different speed levels. In actual environments, the relationship between physical speeds and perceived speeds is non-linear [36], [37], [38], [39]. Hence, the nonlinearity of speed perception should be examined in VR environments, whereas earlier studies have not addressed this problem. We utilized the psychophysical method of magnitude estimation, which allows us to investigate a wide range of speed levels more easily, based on which we can discuss the nonlinearity of speed perception.

Speed perception of moving objects has been extensively studied in psychophysics as a function of spatiotemporal frequencies, for instance, in [15], [16], [18], and [19], where patterned pictures were typically used as visual stimuli. However, the visual stimuli used in our study are markedly different and difficult to compare with those in the literature. VR environments typically involve objects seen in our daily lives, rather than regularly patterned pictures. Moreover, the linearity of speed perception has been understudied in the literature, which has mostly focused on whether apparent speeds are faster or slower than actual. Finally, the effects of perspective conditions are unique to VR environments, and a comprehensive understanding of speed perception of self-motion in such environments may require discussion from different aspects than those used in earlier studies.

As previously mentioned, our study aimed to investigate three objectives related to speed perception in virtual spaces, some of which were partially examined in our previous study [40]. In the present study, we further explored the effects of the textured-wall condition and the influence of viewpoint by using immersive VR goggles.

II. METHODS

A. ETHICAL STATEMENT

This study was approved by the Institutional Review Board, Hino Campus, Tokyo Metropolitan University (H22-054).

B. VIRTUAL SPACE

To investigate speed perception in virtual environments, we constructed a virtual hallway using Unity (Unity 2020.3.12f1, Unity Technologies Co. Ltd., USA). Fig. 2 presents the view from the starting point in each of the six conditions. The upper and lower rows show the first- and third-person views, respectively. The left, center, and right columns show a bleak hallway, object-filled hallway, and textured-wall hallway, respectively. The bleak hallway has a smaller optical flow and dimensional cue. It is equipped with windows as minimum cues to judge the locomotive speed. Participants cannot judge the speed without any visual information, such as windows, embedded in the environment. The object-filled hallway provides a large optical flow and dimensional cue. Size-imaginable objects including shelves, desks, chairs, and plants were arranged on both sides of the hallway between two neighboring windows. The textured-wall hallway provided a large optical flow but a limited dimensional cue. The texture did not look like specific materials and was unlikely to cause participants to imagine the dimensions of surface roughness.

The avatar moved straight in the hallway with no directional change. The length, width, and height of the hallway were 150 m, 4.0 m, and 3.0 m, respectively, and the height of the avatar providing the first- and third-person views in Fig. 2 was 1.6 m. The distance between the centers of two neighboring windows was 24 m and the width of the window was 1.8 m. These dimensional values were not disclosed to the participants. The camera in the virtual space was set between the avatar's eyes for the first-person view, and 5 m behind the center of the avatar's eyes for the third-person view.

C. APPARATUS

The participants were seated on a chair and wore an Oculus Quest 2 VR headset (Oculus VR, LLC., CA. 1832 × 1920 pixels per eye) during the experiment. The headset position was adjusted by the participants while viewing the hallway used in the experiment. The refresh rate measured with the experimental setting was approximately 80 Hz. Communication between the headset and personal computer was through a USB cable for stabilizing the animation.

D. PROCEDURES

We used the psychophysical method of magnitude estimation with a reference stimulus. In this design, participants compared the reference stimulus with each test stimulus. Participants then indicated how many times the intensity of the test stimulus felt stronger or weaker than that of the reference stimulus. For example, if the speed of a test stimulus felt half as fast as the reference, the answer would be 0.5. Participants were only allowed to give positive values as answers.

The reference stimulus was the 1.0 m/s condition of the first-person perspective in the bleak hallway. Nine speed levels ranging from 0.4 to 2.8 m/s with an interval of 0.3 m/s were used as test stimuli in six conditions: the bleak hallway, object-filled hallway, and textured-wall space from two viewpoints. Hence, a total of 54 (9 velocity levels × 3 hallways × 2 viewpoints) observations were made. For all conditions, the stimulus lasted 15 s, during which the moving speed remained constant. After viewing the reference stimulus, participants viewed a randomly presented test stimulus and evaluated how many times faster the test stimulus was compared to the reference stimulus. They watched the reference stimulus before each test stimulus was presented. After every 18 test stimuli, participants took a five-minute break, at which they were asked if they experienced any discomfort to suspend or cease the experiments. In total, it took approximately 90 min for individuals to complete the task.

E. PARTICIPANTS

Thirty university students (in their 20s, 13 females) participated in the task after providing written informed consents. All participants were paid 1,090 JPY/hour and not informed of the purpose of the experiment. Two of the participants owned VR headsets and used them daily. The others had used the VR headset a few times.

F. ANALYSIS

The perceived speeds obtained in the experiment were modeled using Stevens' power law [35];

$$v_p = kv_n^a \tag{1}$$

where v_p and v_n are the perceived and nominal velocities in the virtual space, respectively. k and a are the constants that represent the characteristics of their relationship. We are particularly interested in a that denotes the linearity between the perceived and nominal velocities. The value of a being close

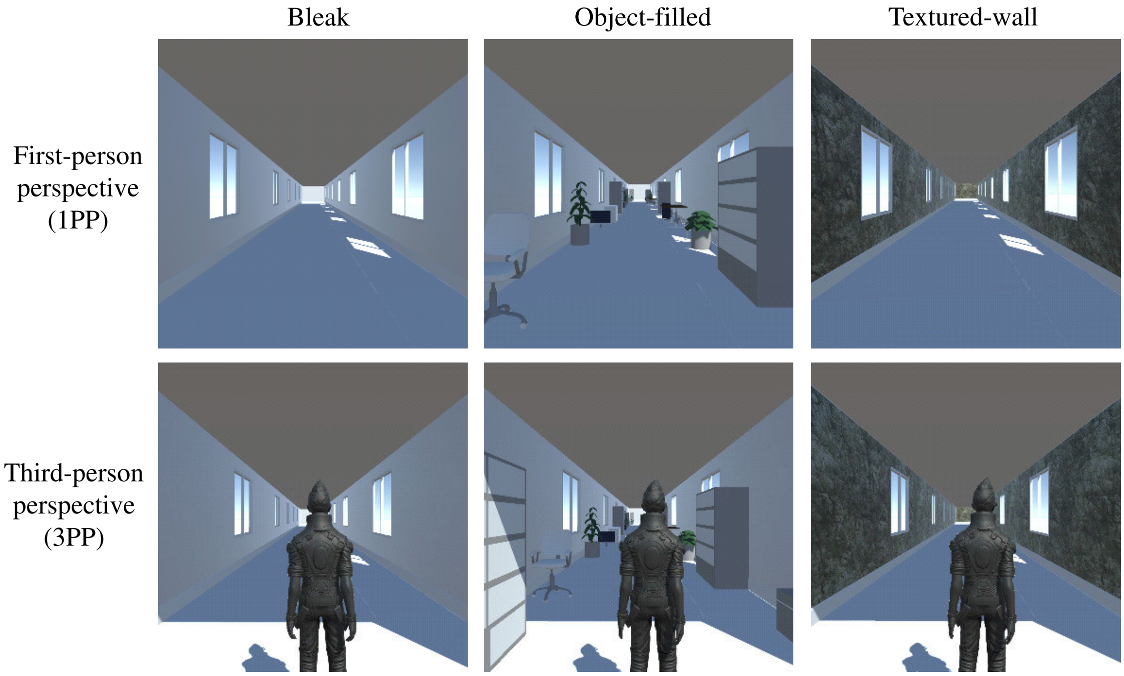

FIGURE 2. Virtual spaces. The top row shows the first-person view and the bottom row shows the third-person view. The left, center, and right columns show a hallway with no objects, a hallway with furniture and other objects, and a hallway with textured walls, respectively.

to 1 indicates a linearity of speed perception. The formula indicates that the relationship between physical quantities and corresponding perceived intensity follows a power function. This allows us to model the velocity perception across a wide velocity range. To compute the two constants using a linear regression analysis, the natural logarithm of (1) was used as follows:

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

The results of each participant were fitted to this equation, and the values of $\log k$ and a were estimated for each individual participant using the least-square method. A t-test was used to determine whether the mean coefficients were significantly different from 0, and whether they differed across experimental conditions. Paired t-tests were applied to two of the three background conditions for the same viewpoint, or to two viewpoints for the same background condition. In the former case, a Bonferroni correction of a factor of three was applied for multiple comparisons.

To investigate the determinants of velocity perception, we applied three-way analysis of variance (ANOVA) with nominal velocity, hallway condition, and perspective condition as factors. For this purpose, we used the *anovan* function of Matlab (2023a, MathWorks Inc., MA). The results are summarized in Table 1. A significant interaction between nominal velocity and hallway condition was observed ($F(16, 1520) = 4.71$, $p < 0.001$). Therefore, we conducted a post-hoc analysis by applying one-way ANOVA for each velocity level with the hallway condition or perspective condition as a factor, with Bonferroni correction for multiple comparisons. We applied the correction factor of nine, which is the number of speed levels.

TABLE 1. Summary of three-way ANOVA with the nominal velocity, hallway conditions, and perspective conditions being factors. d.f. indicates the degree of freedom.

Factor	d.f.	Sum of squares	F	p
Perspective	1	0.119	1.48	0.22
Hallway	2	6.7	41.6	< 0.001
Nominal velocity	8	330.9	514.5	< 0.001
Perspective × Hallway	2	0.25	1.55	0.21
Perspective × Nom. velocity	8	0.88	1.36	0.21
Hallway × Nom. velocity	16	6.06	4.71	< 0.001
Error	1520	122.2		

III. RESULTS

The means and standard errors of the coefficients of Stevens' power law in (2) are shown in Table 2. t- and p-values are also reported to test whether they are significantly different from 0. Table 3 displays the results of the t-test between the three hallway conditions and the two viewpoints for each coefficient.

A. COMPARISON BETWEEN THREE HALLWAY CONDITIONS

Here, three hallway conditions were compared for the same viewpoint condition.

As shown in Table 2 (a), the $\log k$ values in the first-person perspective were -0.10, -0.089, and 0.0068 for the bleak, object-filled, and textured-wall hallways, respectively. Table 3 (a) shows that the value for the textured-wall

TABLE 2. Regression coefficients in (2) for six experimental conditions. (a) and (b) show the coefficients for the first-person perspective. (c) and (d) show those for the third-person perspective. The standard errors, *t*- and *p*-values are also listed.

(a) First-person view: $\log k$

	$\log k$ (k)	s.e.	t	p
Bleak	−0.10 (0.90)	0.014	−7.23	< 0.001
Object-filled	−0.089 (0.91)	0.017	−5.20	< 0.001
Textured-wall	0.0068 (1.00)	0.018	0.38	0.70

(b) First-person view: power exponent a

	a	s.e.	t	p
Bleak	0.64	0.020	31.5	< 0.001
Object-filled	0.76	0.025	30.1	< 0.001
Textured-wall	0.68	0.026	26.0	< 0.001

(c) Third-person view: $\log k$

	$\log k$ (k)	s.e.	t	p
Bleak	−0.20 (0.82)	0.020	−9.80	< 0.001
Object-filled	−0.082 (0.92)	0.016	−5.16	< 0.001
Textured-wall	−0.071 (0.93)	0.018	−3.92	< 0.001

(d) Third-person view: power exponent a

	a	s.e.	t	p
Bleak	0.80	0.030	26.7	< 0.001
Object-filled	0.77	0.023	29.2	< 0.001
Textured-wall	0.77	0.026	30.5	< 0.001

condition was significantly greater than those for the bleak and object-filled conditions. As shown in Table 2 (b), the values of a were 0.64, 0.76, and 0.68 for the bleak, object-filled, and textured-wall hallways, respectively. Table 3 (a) shows that the object-filled hallway condition had a significantly greater a value than the bleak and textured-hallway conditions. However, no significant difference was found between the bleak and textured-wall conditions. Therefore, in the object-filled condition, speed perception was more linear compared to the other conditions.

In Table 2 (c), the $\log k$ values for the third-person view were −0.20, −0.082, and −0.071 for the bleak, object-filled, and textured-wall hallways, respectively. Table 3 (b) indicates that the value for the bleak condition was smaller than those for the other conditions. Similarly, Table 2 (d) shows that the a values were 0.80, 0.77, and 0.77 for the bleak, object-filled, and textured-wall hallways, respectively. Table 3 (b) indicates that there were no significant differences in the a values between the hallway conditions.

Fig. 3 (a) illustrates the magnitudes of perceived speed and the regression curves based on Stevens' power law for the first-person perspective. The regression curves were $v_p = 0.90\, v_n^{0.64}$, $v_p = 0.91\, v_n^{0.76}$, and $v_p = 1.00\, v_n^{0.68}$ for the bleak, object-filled, and textured-wall hallways, respectively. Significant differences in reported speeds between the hallway conditions were observed at some speed levels, specifically at 0.4 m/s, 1.9 m/s, 2.5 m/s, and 2.8 m/s.

Fig. 3 (b) shows the regression curves for the third-person view: $v_p = 0.82\, v_n^{0.80}$, $v_p = 0.92 v_n^{0.77}$, and $v_p = 0.93\, v_n^{0.77}$, for the bleak, object-filled, and textured-wall hallways, respectively. The differences between the hallway conditions were observed at 1.0 m/s, 1.6 m/s, and 1.9 m/s.

B. COMPARISON BETWEEN TWO VIEWPOINTS

Here, the first-person and third-person viewpoints are compared for each hallway condition.

Fig. 4 (a) compares the two viewpoints for the bleak hallway condition. The statistical comparisons are summarized in Table 3 (c). The a value for the first-person view was smaller than that for the third-person view ($p < 0.001$) indicating that the speed perception was more linear for the third-person view. Additionally, there was a significant difference in $\log k$ between the two viewpoints ($p < 0.001$).

Fig. 4 (b) compares the two viewpoints for the object-filled hallway condition. As shown in Table 3 (c), the two viewpoints did not exhibit differences regarding $\log k$ and a values.

Fig. 4 (c) compares the two viewpoints for the textured-wall hallway condition. In the third-person perspective, there was a significant increase and decrease in a and $\log k$ values, respectively, compared with the first-person perspective.

The one-way ANOVA for each speed level did not reveal significant differences in the reported speeds between the two perspective conditions, except for two speed levels in the bleak condition, as shown in Fig. 4 (a).

IV. DISCUSSION

As mentioned in Section I, previous studies on self-speed perception in virtual spaces did not consider a wide range of speeds. In our study, we utilized the method of magnitude estimation and Stevens' power law to investigate the perception of a wide range of speeds. These methods and analyses enable us to discuss the linearity of speed perception. When the exponent is greater than or smaller than 1, the user is hypersensitive to large or small physical or nominal quantities, respectively. When the exponent is close to 1, the perceived and physical quantities exhibit a linear relationship. Previous studies have reported that the exponents of velocity perception in actual spaces range widely from 0.75 to 1.77 [36], [37], [38], [39]. In contrast, the exponents in our study ranged from 0.64 to 0.80 and were below 1 in all hallway and viewpoint conditions. These results are close to or slightly below the lower limit of the previously reported values. Our findings suggest that speed perception in virtual spaces is less sensitive at high speeds. Although the root cause of the variation in the exponent values between earlier studies in actual spaces and our study in an immersive virtual environment is unknown, the type and amount of available perceptual cues may be the cause of the difference.

Fig. 5 summarizes Tables 2 and 3 and shows the exponent a values under all the conditions and their statistical differences. Under the first-person view, between the three types of hallways, the exponent value for the object-filled hallways was largest at 0.76, followed by that of the textured-wall and bleak hallways. The object-filled hallway provided more dimensional cues, resulting in a larger exponent. This hallway condition achieved the most linear velocity perception of the three types of hallway conditions. The exponent for

TABLE 3. Hypothesis tests for log k and a. (a), (b) Comparison between the three hallway conditions for the first- and third-person perspectives, respectively. (c) Comparison between the two different viewpoints for each of the three hallway conditions. Non-adjusted p-values are shown. ** and * indicate significant differences at $p < 0.01/3$ and $0.001/3$, respectively, using Bonferroni correction for (a) and (b). For (c), *** indicates a significant difference at $p < 0.001$ with no adjustment of p-value.**

(a) Comparison between three background conditions: First-person perspective

	Bleak vs. Object-filled	Bleak vs. Textured-wall	Object-filled vs. Textured-wall
$\log k$	$t = 0.64, p = 0.52$	$t = 6.70, p < 0.001$***	$t = 5.49, p < 0.001$***
a	$t = 5.63, p < 0.001$***	$t = 1.91, p = 0.056$	$t = 3.24, p = 0.0012$**

(b) Comparison between two viewpoint conditions: Third-person perspective

	Bleak vs. Object-filled	Bleak vs. Textured-wall	Object-filled vs. Textured-wall
$\log k$	$t = 6.48, p < 0.001$***	$t = 6.71, p < 0.001$***	$t = 0.66, p = 0.51$
a	$t = 1.34, p = 0.17$	$t = 1.17, p = 0.24$	$t = 0.18, p = 0.85$

(c) Comparison between first- and third-person perspectives

	Bleak	Object-filled	Textured-wall
$\log k$	$t = 5.92, p < 0.001$***	$t = 0.41, p = 0.68$	$t = 4.32, p < 0.001$***
a	$t = 6.62, p < 0.001$***	$t = 0.074, p = 0.94$	$t = 3.43, p < 0.001$***

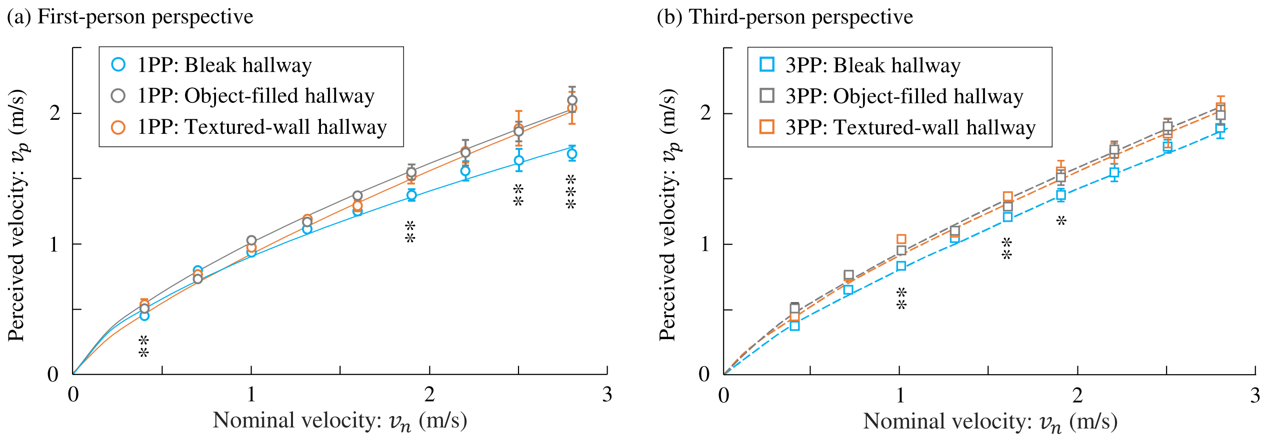

FIGURE 3. Means and standard errors of perceived velocities for three hallway conditions and two different viewpoints. *, **, and * indicate significant differences between the hallway conditions for each velocity level by one-way ANOVA at $p < 0.05$, 0.01, and 0.001, respectively, with Bonferroni correction of factor 9. (a) Three hallway conditions for the first-person perspective. (b) Three hallway conditions for the third-person perspective.**

the bleak hallway was smallest, potentially because both the optical flow and dimensional information were the least. Nonetheless, it must be noted that the mean exponents of the bleak and textured-wall conditions were not significantly different. Further, expectedly, the exponent for the textured hallway was smaller than that for the object-filled hallway. This suggests that the number of size-imaginal objects or dimensional information is important for the linear speed perception. To be more conclusive, further studies are necessary, where, for example, we randomly change the wall texture at every trial such that participants cannot rely on its dimensional information.

Regarding the effect of viewpoints, as shown in Table 3 (c) and Fig. 5, significant differences existed in the exponent a values between the first- and third-person views for the bleak and textured-wall hallway conditions. However, the values for the object-filled hallway did not differ between the first- and third-person perspectives. In other words, for the first-person perspective, the exponents differed among the three hallway conditions; however, such differences diminished for the third-person perspective. These results suggest that the third-person view condition potentially obscures the differences in the a values or linearity of speed perception for the three types of hallways. The avatar's appearance in the third-person view may provide a substantial dimensional cue to judge the speed in the virtual hallway, which is reasonable considering that some earlier studies suggested that the third-person perspective fosters spatial awareness between the self and peripheral objects [29], [30], [31], [32], [33]. The exponents were larger for the third-person perspective than for the first-person perspective for the bleak and textured-wall conditions, and they were closer to 1. This suggests that the third-person view may lead to a more linear relationship between the perceived and nominal velocities in the virtual space.

As previously mentioned, the perspective condition had an impact on the linearity of speed perception; however, it did not significantly influence the magnitude of perceived speed, as shown in Fig. 4. Only for the bleak condition, differences in perceived speed were observed between the two perspective conditions for a few speed levels, as shown in Fig 4 (a). Therefore, the perspective condition was not a major factor

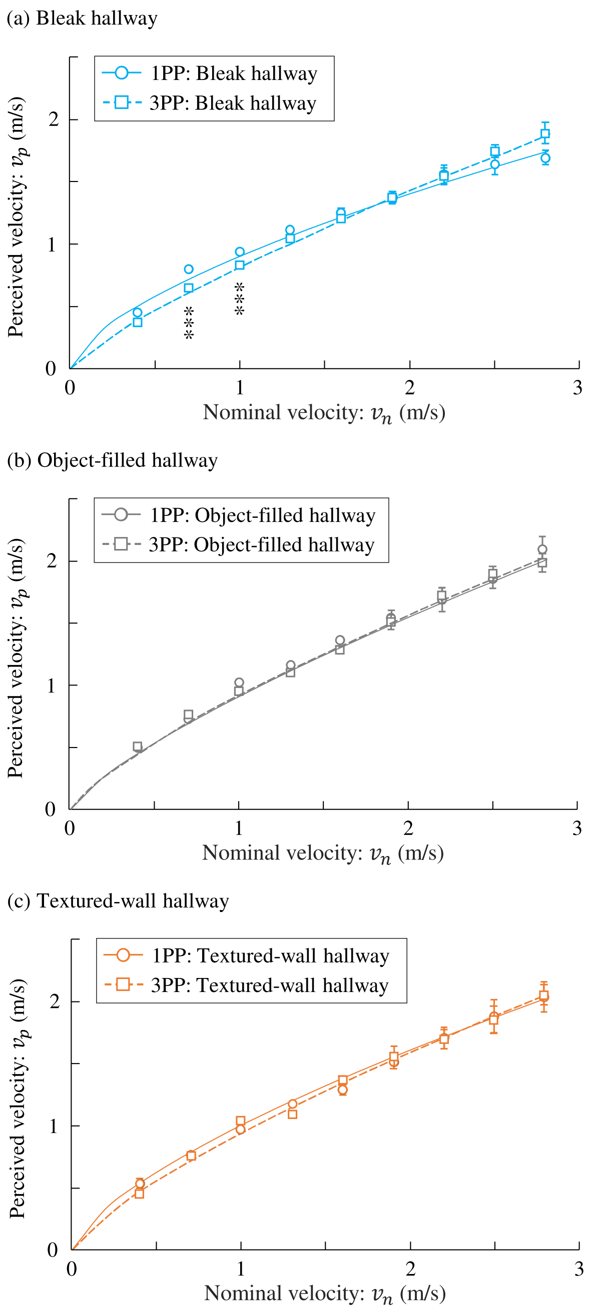

FIGURE 4. Means and standard errors of perceived velocities for each of the three hallway conditions. Rearrangement of Fig. 3 (a) and (b). * indicates a significant difference between the perspective conditions for each velocity level by one-way ANOVA at $p < 0.001$ with Bonferroni correction of factor 9. (a) Bleak hallway at two viewpoints. (b) Object-filled hallway at two viewpoints. (c) Textured-wall hallway at two viewpoints.**

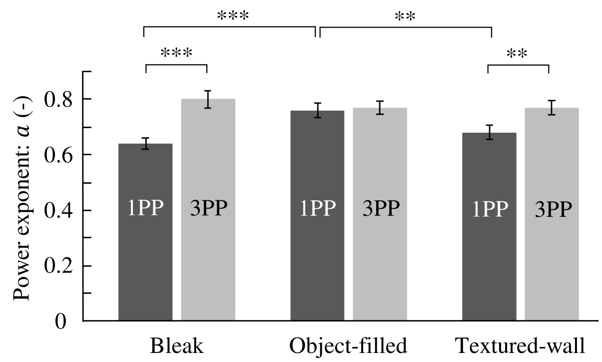

FIGURE 5. Power exponent parameter a for each condition. Graphical summary of Tables 2 and 3. ** and * indicate statistical significances at $p < 0.01$ and 0.001, respectively. 1PP and 3PP mean the first- and third-person perspectives, respectively.**

in determining the magnitudes of speed perception. This was consistent with the results of the three-way ANOVA in Table 1, where the main effect of the perspective condition was not significant. Nevertheless, at speed levels greater than those tested in this study, the two perspective conditions could potentially result in different magnitudes of perceived speed because even a slight difference in the power exponent could lead to a considerable difference at high speed levels.

As shown in Fig. 3, at some speed levels, in the bleak hallway, the perceived speeds were slower than in other hallway conditions. Earlier studies on the effects of contrast and spatiotemporal frequencies of visual stimuli may explain this. In VR environments with low visual contrast, the motion speed is perceived slower [23], though such effects are still under debate [20], [21]. A moving object with a low visual spatiotemporal frequency feels slower [15], [16], [17], [18], [19]. In the bleak condition, with large areas of plain walls, the contrast and spatiotemporal frequency are small. Under this condition, the perceived self-speeds are reasonably small.

There are some limitations that need to be examined in the future. Although several studies have been conducted on speed perception [15], [16], [17], [18], [19], a comparison cannot be made between these studies and the present one because the quality of visual stimuli used in these studies is different from the one used in this study. Typically, periodic gratings defined by their spatial frequency were used in literature, whereas the present study used furniture or plant pots placed in virtual hallways. However, early findings that the increase in spatiotemporal frequency of visual stimuli leads to the increase in apparent speed [15], [16], [17], [18], [19] can partially explain the results of the present study. The object-filled and textured-wall conditions raised the spatial frequency of visual stimuli. However, the hallway conditions in this study were not controlled such that they can be converted into a form comparable with earlier literature. Furthermore, regarding the object-filled hallway condition, it is still unknown what kind of objects and how many objects per unit length influence the speed perception. Regarding the textured wall condition, this study did not investigate the effects of different textures. Speed perception may depend on the textures of the walls.

One of the future aspects of this research is the perception of self-rotational motion. VR environments typically involve such motions and are associated with cybersickness [41], [42], [43], [44], [45]. If the background image of the VR environment influences the speed perception of self-rotational motion, then the background information may impact cybersickness. Although we used straight hallways in this study, where no participants reported discomfort after the experiments, examining the speed perception in settings with turning motions is the next challenge.

Another aspect to be studied in the future is what kind of results are acquired from combining the object-filled and textured-wall conditions. If the speed perception in the combined condition is more linear and perceived intensities are greater than in both the object-filled and textured wall conditions, then we may hypothesize that the objects as dimensional cues and wall textures stimulate different and independent channels of speed perception. If the speed perception under the combined condition is comparable to either of the object-filled or textured-wall conditions, then we may be able to regard one of the two conditions as being predominant.

V. CONCLUSION

Earlier studies have not investigated the perception of self-locomotion speed for a range of speeds under different scenarios and perspective conditions, i.e., first- and third-person perspectives. The three scenery conditions comprising a bleak hallway, an object-filled hallway, and a textured-wall hallway were examined. The perceived velocities were formulated using Steven's power law, of which the power exponent indicates the linearity or nonlinearity between the physical quantity and its perceived intensity. The scenery of hallways influenced the linearity of speed perception. For the first-person perspective condition, the exponent of the object-filled hallway, which included size-imaginable objects on the hallway, was the greatest (0.76) and closest to 1 among the three types of hallways. The exponents for the bleak and textured-wall conditions were comparably small. Further, the perceived intensities were affected by the hallway scenery, and the intensities for the bleak condition were smaller than the other hallway conditions at several speed levels for both perspective conditions. The third-person perspective increased the exponents for the bleak and textured-wall conditions, making the speed perception more linear. As a result, the exponents were not significantly different between different scenery conditions. These findings will assist creators of VR spaces in designing their content. In the future, we will investigate the number and type of size-imaginable objects in the virtual space that are necessary for accurate speed perception.

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