Improvement of speed perception in driving simulators using image deformation based on the human visual space

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Abstract
Driving simulators (DSs) have been widely used to develop advanced driver assistance systems to improve driving safety in vehicles. A major drawback of using DSs is the lack of speed perception while driving. Hence, improvements to speed perception have been recognized as a major priority for enhancing DSs. One approach for achieving better speed perception is to manipulate the human visual space using distorted images in DSs. A previous study revealed that the visual space was distorted subjecting to a visual distance towards an object in a virtual space. Thus, this study aims to obtain optimized image distortions and to evaluate their ability to allow drivers to perceive speed more accurately. A set of computer graphic images representing driving in a straight rural-like road was generated by applying distortions to the original image. The first experiment was conducted to determine the participants’ perceived speeds when viewing the images. Four levels of image distortion were used on seven images representing different speeds. The perceived speed increased with the image distortion, and an equation defining the perceived speed as a function of both image speed and distortion was derived. Another experiment was then conducted to verify whether the images generated using the derived equation could allow drivers to accurately perceive speed. As a result, the optimized image distortion allowed the DS users to accurately determine the image speeds, with an average difference between the perceived and the image speed of 2.7%.

Keywords: Perception of speed, Driving simulator, Human visual space, Driving safety, Computer graphics

1. Introduction

A driving simulator (DS) is an example of a typical virtual reality application. DSs generate a virtual road and traffic environment using computer graphics (CG) and provide a virtual driving experience (Miki, 1992). The Ministry of Land, Infrastructure, Transport and Tourism, and automobile manufacturers have led the development of advanced driver assistance systems, and they release information regarding their evaluations of its effects for DS applications. Thus, the importance of DSs has driven the need for more DS research and development for automobiles. Consequently, the use of DSs have expanded to an area where evaluation experiments conducted using real automobiles are needed (Ishikura and Suzuki, 2017; Scanlon et al., 2016; Hiraoka et al., 2010). However, according to Nerio and Chiku (2006), the following four advantages of using DSs over real automobiles in evaluation experiments were identified.

(1) It is easy to provide a safe and secure environment during the experiment.
(2) Modification of the experimental conditions is easy, and high repeatability is ensured.
(3) More measurable data items, including traffic events and drivers’ performances, are available, and it is relatively easy to obtain such data items.
(4) Systematic and effective use of DS data can be established without the influence of temporal fluctuations, such as the season, weather conditions, and the time of day.

However, when using a DS, speed perception reduces more compared with when a real automobile is used (Kuriyagawa et al., 2004; Hurwitz et al., 2005; Bella, 2008). As a result, participants using a DS tend to drive rather
aggressively, and thus their driving performance is not representative of their behavior in a real vehicle (Kuriyagawa and Kageyama, 2009; Mourant et al., 2007). Therefore, providing an accurate perception of speed in a DS is a major challenge to the effective use of DSs.

There are currently two approaches to reducing the gap between the real and perceived speed in DSs. One methodology is to enlarge the display area to provide a wider range of visibility (Kuriyagawa and Kageyama, 2009; Durkee and Ward, 2011; Mourant et al., 2007) and the other is to introduce motion systems to provide real motion cues in DSs (Reymond et al., 2001). Both methodologies have major drawbacks, which include costly implementation and difficulty in scaling. The use of CG images to improve the perception of speed could be implemented for both large- and small-scale DSs. However, only a few studies (Mourant et al., 2007; Colombet et al., 2010; Diels and Parkes, 2010) have focused on using CG images to improve the perception of speed in DSs. They adopted a minification technique by which a minified CG image was projected without changing the size of image on a screen, and there was empirical evidence to indicate a positive effect of image minification on the perception of speed. However, only a few target speeds were examined, and a static method of image modification was used, so that the modification was the same for all speed conditions.

This study manipulated the geometric characteristics of a CG image to influence the human visual space in order to improve speed perception during DS operation. The visual space is defined as “the space we perceive through vision” (Erkelens, 2015), and the visual space is distorted depending upon the distance from the eye to the visual targets in depth (Cuijpers et al., 2002; Doumen et al., 2005). Hillebrand and Blumenfeld introduced the alley experiment, a classical approach to quantifying the distortion between physical and visual spaces (Erkelens, 2015). In a previous study (Nagata et al., 2008), an approach to distorting the still image with considering the human visual space was demonstrated, and it was found that the perception of distance and object sizes were closer to those in real space. In the case of moving images, Asao et al. (2010) conducted an alley experiment in CG virtual space, where they compared the participants’ visual space when a background image remained unchanged to when the background image was changed to give participants the illusions of moving forward. In the case of a changing background, the study found that the visual space was shifted inward as the visual distance became shorter. The experimental results demonstrated that it is possible to achieve a more accurate perception of speed by deforming CG images.

The objective of this study, therefore, is to empirically verify the hypothesis that improved speed perception can be achieved by distorting CG images to alter a human’s perception of their visual space. This study comprises two experiments. The first investigated the effect of different levels of image distortion on speed perception, and then the second studied the accuracy of the participants’ perceived speed when they observed images with optimized distortion, which was based on the results of the first experiment.

2. Experiment 1: Speed perception under distorted image conditions

2.1 Characteristics of the distortion applied to the image

The human visual space shifts inward as the visual distance becomes shorter (Erkelens, 2015; Asao et al., 2010). To apply deformations to the CG images, the relationship between the horizontal and depth positions in the distorted visual space needed to be defined. $P (x, y, z)$ is a point in the visual space prior to deformation, and it is converted to $P_d (x_d, y_d, z_d)$, which is a point in the distorted visual space. Each coordinate in $P_d (x_d, y_d, z_d)$ can be calculated as follows:

$$
\begin{bmatrix}
x_d \\
y_d \\
z_d
\end{bmatrix} = \begin{bmatrix}
a|x|+b & 0 & 0 \\
0 & a|y|+b & 0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
x \\
y \\
z
\end{bmatrix}
$$

(1)

where $x$, $y$, and $z$ are coordinates in the pre-deformed visual space, and the $z$-axis is the anteroposterior axis. $x_d$, $y_d$, and $z_d$ are coordinates in the deformed visual space. The constants $a$ and $b$ represent the intensity of deformation.

The visual space in the virtual world was shifted 30% inward at a visual distance of 2 m (Asao et al., 2010). In this study, four levels of deformation intensities were evaluated, which are determined by the constants $a$ and $b$. At the $a$ and $b$ values listed in Table 1, the location of any object’s vertices in the CG image were undistorted or distorted by 40%,
60%, or 80% inward relative to the original location of the vertices. The relationship between the horizontal and depth distances using the coordinate transformation is shown in Fig. 1. Figure 2 shows four typical images; one is the image without deformation and the others were generated with 40%, 60%, and 80% inward deformation. Comparing the four images in Fig. 2, distortion is most apparent along the white center line, which appears to stretch as more distortion is applied to the image.

The subjective speed of DS drivers is involved by eye height (Warren, 1982; Larish and Flach, 1990; Flach et al., 1997), texture (Blackmore and Snowden, 2000; Nguyen-Tri and Faubert, 2007; Manser and Hancock, 2007), visual field (Brandt et al., 1973; Jamson, 2001), image contrast (Blackmore and Snowden, 1999), brightness (Takeuchi and Valois, 2000), vection (Brandt et al., 1973), resolution (Anderson, 2011) and refresh rate (Anderson, 2011) in an aspect of the visual information. All of them can be explained by or related to optic flow (Gibson, 1950; Larish and Flach, 1990; Mourant et al., 2007), which is an apparent vector field of motion of the surrounding objects. The proposed image deformation can increase the optic flow caused by the objects especially near the driver, therefore, it is a suitable method to increase the subjective speed in DS.

Table 1  \(a\) and \(b\) constant values used for the different levels of image deformation studied.

| Intensity          | \(a\)      | \(b\)      |
|--------------------|------------|------------|
| No deformation     | 0.0        | 1.0        |
| Deformation-40%    | \(0.4 \times 10^{-3}\) | 0.6        |
| Deformation-60%    | \(0.6 \times 10^{-3}\) | 0.4        |
| Deformation-80%    | \(0.8 \times 10^{-3}\) | 0.2        |

Fig. 1  Sets of points deformed at four intensities of deformation using constants \(a\) and \(b\) listed in Table 1. Distances were calculated from the origin, which is the midpoint between two eyes in a horizontal plane. Longitudinal straight lines, corresponding to \(x = \pm 1.0\) of lateral positions or \(y = \pm 1.0\) of vertical positions, respectively, under no deformation condition were deformed inward as the depth distance became closer when more deformation was applied.

2.2 Participants

A total of 15 university students, 13 of which were males and 2 were females, participated in the study with informed consent. They reported normal or corrected-to-normal vision, and they all possessed a valid driver’s license. An internal review conducted by an ethics committee for experiments with human participants approved the procedures used in the experiments.
Fig. 2  Typical CG images generated by the conversion of deformation at the same position in the virtual world. The image with no deformation, 40%, 60%, and 80% deformation are shown from left to right. The red circle in the middle of each image is the fixation point. The upper images are the same as used in the experiments. The lower images are typical examples when buildings are located along the road.

2.3 Apparatus

Figure 3 illustrates the experimental setup. The eye-point was prepared to match the actual vehicle eye-point, and the horizontal and vertical field of view (FOV) provided by the setup were 49° and 37°, respectively. The experimental environment consisted of an image generator (customized PC, APPLIED Corp. Graphics: ELSA EQK620-2GER), an liquid crystal projector (EMP-1825, EPSON Corp. Refresh rate: 60 Hz), and a 100-inch screen (SRMS3D-100, Solidray Co., Ltd.). The windows in the experimental room were covered with black curtains to remove external light, and all lights were turned off.

The CG image was generated using OpenGL, and the deformation of the image described in Section 2.1 was implemented as a vertex shader using GLSL. The image consisted of a simple view of a straight rural-like road, with a green lawn area on both sides of the road, as shown in the upper of Fig. 2. Sky and mountains were present in the top portion of the image, and no vehicles or obstacles were on the road.
2.4 Task

Participants were seated with their heads set on a chin-rest (T.K.K.930a, Takei Scientific Instruments) to ensure the height of their eye-point was 1.3 m from the floor, and the distance from the screen was 1.5 m from the center of the projected images. In the practice session, sample CG images were shown for 5 s followed by a gray masking image for 5 s. When viewing the grey image, participants were asked to verbally report their perceived speed in km/h when they were viewing the previous CG image. Participants were instructed to look at a red fixation point during the experiment, which was presented with a size of 1° in the middle of the image. No feedback information regarding the accuracy of their responses was given to the participants. One CG image and one grey image were considered one trial, and at least 28 trials were conducted in the practice session, which can be broken down to four levels of deformation for seven image speeds of 1, 20, 40, 60, 80, 100, and 120 km/h. After 28 trials, the practice session was continued until participants felt comfortable with the procedure for estimating the speed of the CG images.

After the practice session, the actual experiments started. The experiments included five sessions, and each session consisted of 28 trials for the four levels of deformation on the seven image speeds. The procedure for the trial was identical to the one used in the practice session. The order of the trials was fully randomized within a session. The conditions at speeds of 1 km/h and 120 km/h were dummies to avoid regression bias, in which observers are reluctant to make extremely low or high judgments, even though their perception may be correct (Gescheider, 1997).

2.5 Data analysis

The effects of deformation (four levels) and image speed (five levels) on the perceived speed were tested with five repetitions using a within-participants design. A two-factor repeated measure analysis of variance (ANOVA) was used to analyze the effect of deformation and image speed.

2.6 Results

Results of the two-way ANOVA on the perceived speed revealed that the perceived speed was significantly affected by the image speed ($F(4, 1480) = 323.14, p < 0.001$), the level of deformation ($F(3, 1480) = 397.60, p < 0.001$), and the interaction of the image speed with the level of deformation ($F(12, 1480) = 4.93, p = 0.001$). Excluding the images for 1 and 120 km/h, the average error of the perceived speed, which were calculated by (perceived speed − image speed) / image speed × 100, were -54.2% for images with no deformation, -35.0% at 40% image deformation, -16.7% at 60% image deformation, and 20.5% at 80% image deformation. The relationship between the CG image speed and perceived speed at different deformation levels is shown in Fig. 4. The left figure shows the geometric mean across participants, with the error bars indicating their standard errors. The dashed line in the figure shows the case when the CG image speed and perceived speed are identical. As shown in the figure, the perceived speed increased with the level of deformation. Only in the case of 80% deformation were some of the reported perceived speeds greater than the CG image speed. According to the results of the experiment, it is clear that the perceived speed can be changed in DSs if an appropriate level of deformation is performed on the original image.

Subjective sensation can be expressed as a power function of a physical stimulus (Stevens, 1986). To derive the perceived speed $V_p$ as a function of both the image speed $V_g$ and deformation level, a least-square approximation was conducted. As a result, the following equation was obtained ($R^2 = 0.986, p < 0.001$).

$$V_p = 10^{0.0438 V_g^{0.754} (1-\alpha)^{0.617}}$$

where $\alpha$ is the deformation ratio with values of 0.0, 0.4, 0.6, or 0.8 for no deformation, 40%, 60%, and 80% deformation, respectively. Solving this equation for $\alpha$, appropriately deformed images could be generated that would be perceived as an arbitrary speed $V_p$ while the actual image speed would be $V_g$. The purpose of the next experiment, detailed in the following section, is to determine if the optimized image deformations can cause the perceived speed to match with the real speed when driving an automobile.
Fig. 4  Relationship between motion speed generated by CG images and perceived speed (left), and the error rates of the perceived speed to the image speed (right) at different deformation levels, which was obtained using (perceived speed − image speed) / image speed × 100. The dashed line on the left figure shows the condition when the perceived speed matches the CG image speed.

3. Experiment 2: Evaluation of the optimal image deformation

3.1 Parameters

Similar to in DSs, drivers also underestimate their driving speed in real automobiles. However, they perceive a lower speed in a DS than when driving in a vehicle (Hurwitz, 2005; Bella, 2008). Evans (1970) investigated participants’ subjective speed in a real automobile and derived a psychophysical function of speed. The equation derived by Evans (1970) was used in this experiment to measure the ability of the optimized image deformation to influence an observer’s speed perception. The equation is as follows:

\[
V_p^* = 0.324 V_g^{1.145}
\]  

(3)

where \( V_p^* \) is the perceived speed when the automobile moves at the real speed of \( V_g \). By equating \( V_p^* \) in Eq. (3) to the \( V_p \) in Eq. (2), the deformation ratio \( \alpha \) can be obtained, where the DS drivers should perceive the speed as \( V_p^* \) for an arbitrary image speed of \( V_g \). The parameters \( a \) and \( b \) for the deformation of the image can now be calculated, since both parameters are proportional to the deformation ratio \( \alpha \). Table 2 summarizes these parameters at different target speeds \( V_p^* \) that participants would perceive when viewing a CG image with speed of \( V_g \).

| CG image speed \( V_g \) [km/h] | Target speed \( V_p^* \) [km/h] | Deformation ratio \( \alpha \) | Parameter \( a \) | Parameter \( b \) |
|-------------------------------|---------------------------------|-------------------------------|-----------------|-----------------|
| 20                            | 10.0                            | -0.095                        | -0.95 × 10^{-4} | 1.095           |
| 40                            | 22.1                            | 0.294                         | 2.94 × 10^{-4}  | 0.706           |
| 60                            | 35.2                            | 0.454                         | 4.54 × 10^{-4}  | 0.546           |
| 80                            | 49.0                            | 0.545                         | 5.54 × 10^{-4}  | 0.455           |
| 100                           | 63.2                            | 0.605                         | 6.05 × 10^{-4}  | 0.395           |

3.2 Participants

The same 15 participants that took part in previous experimental session were used here as well.

3.3 Apparatus and task

The apparatus was the same as the one used in the first experiment as well as the task and procedure for speed evaluation of the CG images. In contrast to the previous experiment, one session consisted of seven trials, which included
two dummy trials (1 km/h for no deformation and 120 km/h for 80% deformation) to avoid regression bias in addition to the five conditions listed in Table 2.

### 3.4 Data analysis

The objective of Experiment 2 was to evaluate whether or not the optimized image deformation condition can lead participants to accurately match their perceived speed \( V_p \) with the target speed \( V_p^* \). Therefore, a one-sample \( t \)-test was conducted to determine if these two speeds were different.

### 3.5 Results

Figure 5 shows the relationship between the image speed and perceived speed. Each white circle in the figure shows the geometric mean across participants, and the error bars indicate their standard errors. The solid line shows the expected perceived speed, and the black circles show the 95% confidence interval (CI) for each image speed. The average difference between perceived and expected perceived speed was 0.13 km/h, with an averaged error of 2.7%. The paired \( t \)-test between the perceived and target speeds showed that the speed differences were not significant for all image speeds. Table 3 summarizes the perceived speeds obtained in Experiment 2, the results of the \( t \)-test, and the 95% CI.

![Fig. 5 Relationship between the CG image speed and the perceived speed. The white circles show the geometric mean of the perceived speed \( V_p \) across participants, and the black circles show its 95% CI. The solid line shows the target speed \( V_p^* \) to be perceived, which was calculated based on the subjective speed in a real automobile (Evans, 1970). The standard error is shown as error bars for each white point.](image)

| \( V_g \) [km/h] | Target speed to be perceived [km/h] | Mean of the perceived speed \( V_p \) [km/h] | \( t \) (14) | \( p \) | 95% CI |
|-----------------|----------------------------------|----------------------------------|----------|-----|--------|
| 20              | 10.0                             | 9.0                              | −0.83    | 0.420 | 6.5 11.5 |
| 40              | 22.1                             | 24.1                             | 0.94     | 0.364 | 19.7 28.5 |
| 60              | 35.2                             | 36.7                             | 0.51     | 0.621 | 30.4 43.0 |
| 80              | 49.0                             | 50.4                             | 0.44     | 0.664 | 43.4 57.4 |
| 100             | 63.2                             | 66.8                             | 0.93     | 0.366 | 58.5 75.2 |

### 4. Discussion

In Experiment 1, the perceived speed with no image deformation was 54.2% lower than the average image speed. An underestimation of over 50% is in agreement with the results of a previous study (Mourant et al., 2007). Mourant et al. (2007) reported a speed overproduction of 60% at a target speed of 30 mph (48.3 km/h). However, their participants were asked to drive at the target speed, whereas in this experiment, the participants were asked to verbally report their perceived speed when presented a set of CG images. This means that the overproduction and underestimation of speed

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are related because the overproduction of speed was caused by the driver’s underestimation of the vehicle’s speed. Although Diels and Parkes (2010) and Colombet et al. (2010) also reported the overproduction of speed, the extent of overproduction was only 8.9% at a target speed of 30 mph (48.3 km/h), and 10% at target speeds of 50 km/h and 90 km/h. This large difference in the underestimation or overproduction can be explained by the difference in the FOV (Diels and Parkes, 2010). The simulators had a horizontal FOV of 150° and 210° in the studies by Colombet et al. (2010) and Diels and Parkes (2010), respectively, whereas the FOV of the simulators was 45° and 49° in the study by Mourant et al. (2007) and in this study, respectively. A limited FOV has consistently been shown to lead to lower subjective speeds (Salvatore, 1968; Jamson, 2001; Kuriyagawa and Kageyama, 2009).

From the ANOVA in Experiment 1, the image speed, deformation level, and the interaction of these two factors had a significant effect on the perceived speed. Mourant et al. (2007) changed the geometric field of view (GFOV), which is the FOV of a camera in a virtual scene. In their experiments, they did not change the size of projected image, therefore, the minified CG image was presented when the GFOV was larger than the FOV. Moreover, they changed the optic flow by placing trees along the edges of the straight road. The study revealed that the interaction between the target velocity and the GFOV was highly significant on the produced speed in addition to the main effects of target velocity, optical flow, and GFOV. In contrast with these results, Diels and Parkes (2010) reported that no interaction effects between the target speed, environment (rural or urban), and GFOV were observed, while the effect of the GFOV was significant. Therefore, static changes in the GFOV increases the subjective speed in a DS for all driving speeds. This difference in the interaction significance may not only depend on the width of the FOV but also other speed clues simulated in DSs.

In the study by Diels and Parkes (2010), the fidelity of DSs was high because their DS provided the driver with information regarding the road and traffic using vehicle vibrations and engine sounds. In the study by Colombet et al. (2010), the DS also had a 6-degree-of-freedom motion platform. On the other hand, in this experiment and in the study by Mourant et al. (2007), the DS supplied no sound or vestibular information. However, the proposed technique used in Experiment 2, where the deformation ratio was changed in accordance with the image speed, is effective for low-fidelity DSs that offer only visual information and a restricted FOV.

In previous studies by Diels and Parkes (2010) and Colombet et al. (2010), the experiments were designed to determine the optimal ratio of GFOV to FOV where the produced speed would match the image speed. However, drivers often produce speeds higher than the target speed in real automobiles (Hurwitz, 2005; Bella, 2008). Therefore, in Experiment 2 of this study, it was examined whether the speed perception was well matched with real automobiles when applying the optimal deformation to the CG image. In the results, the participants perceived the image speed to be the same as the target speed to be perceived. This suggests that the use of optimal image deformation for each image speed is an effective technique for low-fidelity DSs. However, the parameters of deformation shown in Table 2 might change if the FOV of DS is different from that in this paper because the perceived speed is depending upon the optic flow of the images (Gibson, 1950; Larish and Flach, 1990; Mourant et al., 2007). This point is a limitation of this paper, therefore, it is needed that the optic flow should be evaluated objectively by such as image processing, and clarify a relation between the optic flow and perceived speed. Moreover, there is another limitation in this paper. An apparent curvature of the road will change by applying the proposed deformation running on a curved road. Therefore, an algorithm applying the deformation along the curve should be developed.

In Experiment 2, it was aimed to reproduce the perceived speed matched with the real speed reported by Evans (1970). Evans conducted his experiments by using a sporty sedan, however, the height of an eye-point was not described in his paper. A general sedan was simulated in this paper, therefore, the eye-point of participants and a virtual camera were set at 1.3 m from the ground. Although the difference in the eye-point might be small between Evans’ and this study, the eye height in DS and in a real automobile should be the same because the eye height influences the perceived speed (Warren, 1982; Larish and Flach, 1990; Flach et al., 1997).

The perception of the following distance between oneself and a car ahead is also important, and in future work, we intend to investigate whether distance perception changes with image deformation. Moreover, whether or not the image deformation affects a driver’s behavior with traffic, events, and road geometry will be investigated.

5. Conclusion

To improve the perception of speed in a DS, the use of image deformation to distort the visual space of humans was empirically examined. In the no deformation condition, the speed was underestimated by 54.2%. Improved speed...
perception was observed with image deformation, as shown by underestimations of 35.0% and of 16.7%, for 40% and 60% deformation, respectively, and an overestimation of 20.5% for 80% deformation. In contrast with previous studies that used high-fidelity DSs, the interaction of the image speed and image deformation level had a significant effect on the perceived speed. Using these results, an optimal deformation ratio was calculated for each different image speed, and participants were able to accurately match their perceived speeds to the actual speed when driving an automobile.

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