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Mid-air image's background changes the impression of a mid-air image

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Abstract

Previous research in perceptual science has shown that peripheral information can easily change the perception of an object. However, mid-air images are rarely used as targets in such studies. In this study, we placed the ground below a mid-air image and investigated how changing the ground image affected the perception of the mid-air image. Specifically, we confirmed through psychophysical experiments that shadow length variation changes depth perception (Experiment 1) and that the relative motion of a mid-air image and the ground image changes speed perception (Experiment 2). The results of Experiment 1 showed that increasing the shadow length from its exact value increased the perceived depth of the mid-air image by 16% while decreasing the shadow length from its exact value decreased the perceived depth of the mid-air image by 26%. The results of Experiment 2 showed that the perceived speed of the mid-air image when the ground was moving in the opposite direction of the mid-air image was 58% faster than the perceived speed when the ground was moving in the same direction. We expect that the grounds created in this study can extend the range of depth and speed perception in content designs using mid-air images.

CCS Concepts

• ***Computing methodologies*** → ***Perception; Mixed / augmented reality;***

1. Introduction

Figure and ground are essential concepts that often appear in perceptual experience. When we perceive an object with multiple separate areas, these areas are separated into shape (= figure) and background (= ground) for interpretation [ZFVDH00]. The figure is the area of consciousness and interest, and the ground is the area behind and around the figure.

The ground has a significant influence on the interpretation of a figure. In other fields (e.g., comics and animation), many ground expressions change an impression of a character. Examples include expression of speed in speed lines [CRG86,KM08] and background scrolling [TS75,NNTL96], and non-photorealistic motion blur that emphasizes movement [HL94]. These expressions can change the impression of a character easily.

However, whether such ground representations have a similar effect on the perception of mid-air images has not been well studied [KTY*14]. Therefore, we apply the concept of figure and ground to mid-air images to investigate how the characteristics of the ground affect the perception of mid-air images. To apply the concept of figure and ground to a mid-air image, a background surface was placed under a mid-air image, allowing the characteristics of the background to be changed.

Mid-air images have two characteristics: (1) they can be placed together with real objects, and (2) they can move in 3D space. Mid-air images do not use a screen for display, so real objects can be placed around the mid-air image. However, viewers have difficulty perceiving the depth of mid-air images than the depth of real objects. To solve this problem, using a 3D display as a light source can add depth to a mid-air image, however, the performance of the binocular parallax limits depth. A mid-air image can also be moved three-dimensionally by moving the light source. However, when a fast-moving mid-air image is displayed, it quickly becomes invisible due to its limited display area. Therefore, in content that uses mid-air images, there is a limit to the speed at which the mid-air images can move.

Therefore, we investigated whether presenting an image directly below the mid-air image would affect its perceived depth range and movement speed. In conventional methods, this is modified by binocular disparity and changing the movement speed of the light source. Specifically, two types of changes are confirmed by psychophysical experiments: changes in perceived depth due to shadow projection with different lengths, and changes in perceived speed due to motion contrast between a mid-air image and the ground. We believe that using this study's findings will make it easier to design mid-air image contents because it can extend the perceptual range for depth and speed.

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2. Related Work

2.1. Mid-air image

A mid-air image is an image formed in real space by the reflection or refraction of light from a light source. Techniques for forming mid-air images include the Dihedral corner reflector array (DCRA) [MNM06], a Micro Mirror Array Plate (MMAP) [Ots14], Roof Mirror Array (RMA) [KO18], or Aerial Display with Aerial Imaging by Retro-Reflection (AIRR) [YYA*14]. Mid-air images can be observed with the naked eye and, by making the observer unaware of the presence of the display device, make the image seem as if it were present in the space. This study uses MMAP, which is easily available and has relatively high brightness, among all mid-air image-forming optical elements.

Since mid-air images are not materially present, they do not block light and create shadows. Therefore, to cast a shadow of a mid-air image, it is necessary to project an image that imitates the shadow created in the real world using a projector or other means [KTY*14].

2.2. Perceptual changes with shadow

Several researchers have studied the change in perceived object position (in height and depth) by changing the shadow position, and the perceived size of objects depending on the shape of the shadow. Kersten et al. [KKMB96] reported that projecting a moving shadow in the spatial neighborhood of an object creates a strong illusion of dynamic levitation of a stationary object, despite the absence of other depth cues to the object. Such spatial manipulation of shadows changes a photograph's three-dimensional arrangement of objects [KM14]. Kawabe et al. [Kaw19] has created the illusion of a floating object by projecting a shadow on a real two-dimensional object. Sugano et al. [SKT03] showed that shadows are a cue for perceiving the depth position of multiple objects fast and easily in an HMD environment. Kim et al. [KTY*14] reported that projecting a shadow on a mid-air image makes it easier to determine the depth position of the mid-air image. Wanger [Wan92] also reported that shadow is a strong cue to the three-dimensional shape of an object, and that blurred shadow edges make it difficult to perceive the shape of an object.

Based on these findings, we hypothesized that if changing the position of the shadow can change the perceived depth position of an object, then changing the size of the shadow can also change the perceived depth size of the object. As for changing the size of shadows, it is difficult to change the size of shadows created by real objects, but since a mid-air image does not create a shadow, shadows of any shape may be projected. The difference from Kim et al.'s study [KTY*14] is that they showed that projecting a shadow on a mid-air image facilitates a depth-position perception of the mid-air image, while our experiment investigated the change in the perceived depth size of the mid-air image due to the shadow shape.

2.3. Perceptual changes due to relative motion

In the information processing of a moving object, relative motion affects perceiving the object's apparent speed. For example, a stationary stimulus may appear to move in the opposite direction of

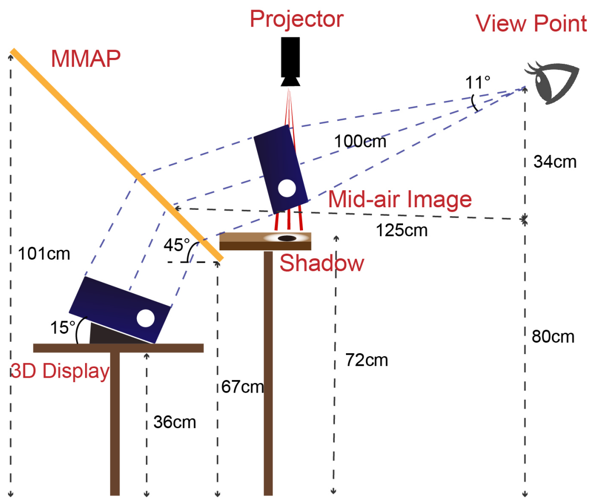

Figure 1: *Optical design; a projector is used to project a shadow directly below a three-dimensional mid-air image using a 3D display.*

peripheral motion. At the boundary between motions with different speeds [WP74], the more emphasized speed difference is perceived, and even objects moving at the same speed are perceived as moving at different speeds if the peripheral motion speed is different [LN73]. This phenomenon is called motion contrast.

The apparent speed of a moving target is reduced when the surrounding stimulus as an inducing stimulus moves in the same direction as the direction of the target, and the effect is strongest when the target and the surrounding are moving at the same speed. When the target and surrounding stimulus are in opposite motion, there are both reports of an increase [TS75] and a decrease [NNTL96] in perceived speed. The decrease is thought to involve motion assimilation, which induces the perception of motion in the same direction as the inducing stimulus, not motion contrast. Thus, relative motion has a strong influence on the apparent speed of an object's motion.

Based on these findings, we hypothesized that the apparent speed of mid-air images can be changed by using motion contrast, which is an effective cue for speed perception.

3. Experiment 1: Depth illusion of mid-air images by changing shadow length

The purpose of this experiment was to determine how varying the length of a shadow under a mid-air image affects depth perception.

3.1. Design of experimental setup

This system used a projector to project shadows onto the surface below the parallax mid-air image. Figure 1 shows the optical design of the experimental setup, which consists of a 3D display, MMAP, and projector. MMAP forms a mid-air image by recurrently transmitting light emitted from a display. The MMAP was placed at an angle of 45°, the 3D display at an angle of 15°, and the projector

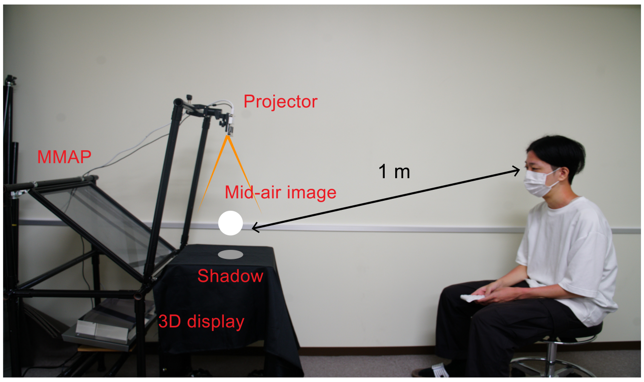

Figure 2: *The actual condition of the experiment*

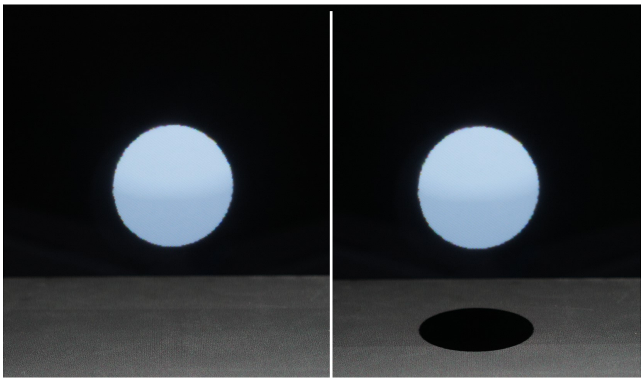

Figure 3: *An example of mid-air images. The left is a comparison mid-air image, and the right is a reference mid-air image with a shadow.*

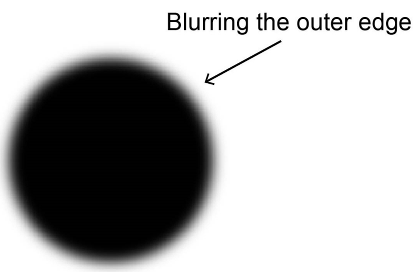

Figure 4: *The shadow image. The shadow edge was slightly blurred.*

was directly above the mid-air image. The viewing distance was set to 1 m in terms of the recommended viewing distance described in the documentation of the Looking Glass used as the display and the binocular disparity effective range [CV95]. The observation position was fixed using a chin rest.

An experimental setup consists of hardware and software to form mid-air images and project a shadow. Figure 2 shows the implementation. The hardware consists of a 15.6-inch Looking Glass from Looking Glass Factory for the 3D display (luminance measured from a viewing distance of 1 m with a white image: $45.3\,\mathrm{cd/m^2}$), an ASKA3D plate from ASKANET for the MMAP (488 mm × 488 mm), and an HD pico laser projector construction kit for Pi for the projector. The software consists of Unity software Ver 2019.4.25f1 to create the images to be displayed on the 3D display and projector.

3.2. Method

We recruited 17 participants (15 males and 2 female), ranging in age from 21 to 27, all of whom were students at the University of Electro-Communications. The Ethical Review Committee of the University of Electro-Communications approved this experiment (ID#21064). The stereo fly test results showed that all participants had stereoscopic functions.

The experiment was conducted in a dark room and used a reference mid-air image, a comparison mid-air image, and a shadow image. The reference mid-air image was a sphere with a diameter of 5.0 cm. The shape of the mid-air image for comparison was an ellipsoid with a horizontal diameter of 5.0 cm, a height diameter of 5.0 cm, and a depth diameter of r cm. r was as follows. r = {1.0, 3.0, 5.0, 7.0, 9.0} [cm] The position of the center of the ellipsoid was the same for all values of r. Figure 3 is an example of presenting mid-air images. The luminance of the mid-air image measured from the viewpoint position was $13.2\,\mathrm{cd/m^2}$. The shadow was an ellipse with a diameter of 4.0 cm in the horizontal direction and r' cm in the depth direction. r' was as follows. r' = {3.0, 5.0, 7.0} [cm] The shadow image was placed directly below the mid-air image, and the center position was the same for any value of r'. In this experiment, two light sources are illuminating the mid-air image; one is a directional light and the direction of the beam is vertical to the ground (Color: white, Intensity: 0.42). The other is environmental light which illuminates the entire mid-air image (Source: Color, Ambient Color: white). The shadow length conditions used in this virtual light source setup (3.0 cm, 5.0 cm, and 7.0 cm) are short, correct shadow lengths, and long shadow lengths, respectively. The shadow edge was slightly blurred using the Gaussian blur function in Adobe Illustrator CC (Version 26.3.1). The shadow image is a circle with a diameter of 195 px and a Gaussian blur radius of 5 px. With this process, the darkest areas of the shadow occupied most of the shadow, while the brighter, blurred areas were only on the edges. Figure 4 shows the shadow image used in the experiment. The shadow luminance measured from the viewpoints was $3.4\,\mathrm{cd/m^2}$. Under this light source setting, the mid-air image also has shading, with a brighter upper part and a darker lower part.

Participants compared the depth of the reference mid-air image with a shadow and the comparison mid-air image without a shadow. The participants were then asked the question, "Of the first and second mid-air images presented, which mid-air image itself had the greater depth?". Participants answered using a keyboard. The reference and comparison mid-air images were displayed randomly, one by one. The display time for each mid-air image was 4 seconds. The combination of shadow length and depth of the mid-air image

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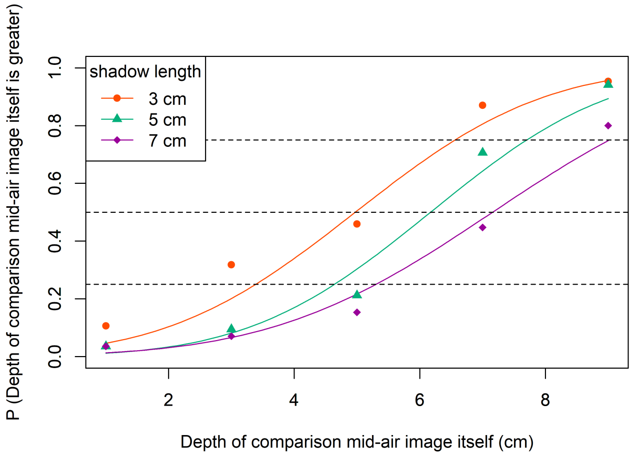

Figure 5: *The percentage of trials in which the depth of the comparison mid-air image itself (1.0, 3.0, 5.0, 7.0, 9.0 [cm]) was reported to be greater than the depth of the reference mid-air image with a certain length shadow (3.0, 5.0, 7.0 [cm]).*

Table 1: *The value of mean PSE and mean 25%DT and mean 75%DT. Values are given as mean ± Standard Error of the Mean (SEM).*

Mean 25%DT	Mean PSE	Mean 75%DT
3.21 ± 0.42	5.00 ± 0.28	6.78 ± 0.53
4.95 ± 0.37	6.14 ± 0.20	7.29 ± 0.22
5.69 ± 0.40	7.20 ± 0.33	8.63 ± 0.39

itself was randomized for each trial. The total number of trials was 75 (3 types of shadow length × 5 types of the comparison mid-air image's depth × 5 repetitions). The duration of the experiment per person was about 20 minutes.

3.3. Results

We calculated and plotted the proportion of trials in which the comparison mid-air image was reported to have greater depth than the reference mid-air image (Figure 5). We fitted a cumulative normal distribution function to the response proportion data for each participant. The depth of the comparison mid-air image at which the participant answered "the comparison mid-air image have greater depth" in 50% of the trials is taken as the point of subjective equality (PSE). The PSE indicates how much the depth (5.0 cm) of the mid-air image with r' cm shadow was perceived as depth. The depth of the comparison mid-air image at which the participant answered "the comparison mid-air image have greater depth" in 25% and 75% of the trials is taken as 25% detection threshold (25%DT) and 75% detection threshold (75%DT), respectively. Table 1 shows the value of mean PSE and mean 25%DT and mean 75%DT.

For PSE obtained from the results of each participant, we ran a one-way repeated measures analysis of variance (ANOVA) with the shadow length condition (3 levels). A Shapiro-Wilk test did not indicate that the assumption of normality had been violated. A Mauchly's test of sphericity indicated that the assumption of sphericity had been violated ($\chi^2(2) = 8.671, p < 0.05$). A one-way repeated measures analysis of variance (ANOVA) using a Greenhouse-Geisser correction found a significant effect on PSE between shadow conditions (F(1.39, 22.24) = 21.449, p < 0.001, partial η^2 = 0.402). Multiple comparison tests (Holm method) indicated that each of the three shadow length conditions was significantly different from the others (p < 0.05).

3.4. Discussion

The results of Experiment 1 showed that as the depth of the shadow increases (or decreases), the perceived depth of the mid-air image that matches it also increases (or decreases). There are several cues to perceive the object's depth such as binocular disparity, kinetic depth effect, and pictorial cues (shade, texture gradient, and contour shape). Under the experimental conditions and viewing distance, binocular disparity, shade, and contour shape were present. Therefore, the change in shadow shape seemed to affect any or all of these three cues, changing the apparent mid-air image depth, but we have not been able to identify which cues were affected. In this regard, we believe that a similar experiment using a 2D display as a light source and only pictorial cues will reveal which cues are affected by shadow size changes.

While this experiment investigated whether changing the length of the shadow projected under the mid-air image changes the depth perception of the mid-air image, other factors must be considered. The first thing to consider is the limits of shadow length and blur, as well as the direction and position of the shadow. It is unclear whether the apparent depth of the mid-air image itself would increase (or decrease) if a shadow of a larger (or smaller) length was displayed, as in this experiment. If the length of the shadow is too large (or too small), the observer may not perceive the displayed black circle as the shadow within a mid-air image. The effect of shadows on depth perception becomes more apparent when examining the threshold of shadow length at which the displayed black circle would be perceived as the shadow of a mid-air image. Previous studies have shown that blurring shadows produces a strong layout illusion [KM14] and negatively affects shape perception [Wan92]. We applied a Gaussian blur with a radius of 5px to a 195px diameter shadow, but the suitable degree of blur is not yet known. As a result of the different directions and positioning of the virtual light source, the shadow projected on the mid-air image may not match the shadow projected on the real object in the real world. By considering these factors in the creation of shadows, shadows may cause additional changes in the depth of the mid-air image itself.

4. Experiment 2: Emphasis of motion in mid-air images by motion contrast

This experiment investigated how the perceived characteristic of a mid-air image motion is changed by the motion contrast between the mid-air image and its ground through relative motion. To evaluate changes in speed perception due to motion contrast, we constructed an environment in which a mid-air image and a ground image could be simultaneously moved and conducted a psychophysical experiment using an adjustment task. We used a mid-air image

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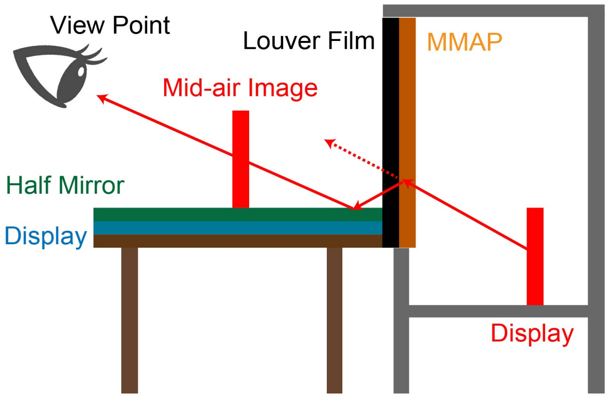

Figure 6: *Optical Design. Light emitted from the display passes through the MMAP and travels to form an image at a position that is plane-symmetrical concerning the MMAP. The light is then reflected by a half-mirror to form an upright mid-air image on the reflective surface. The louver film is placed in front of the MMAP. This makes light that forms mid-air images transmit and light that directly reaches the user's eyes blocked.*

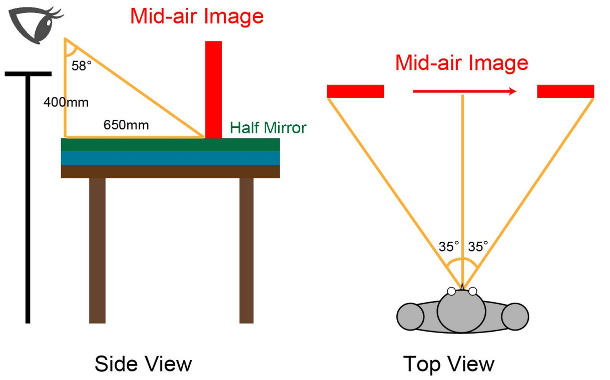

Figure 7: *The positional relation between the mid-air image and the subject's viewpoint. (left) The angle between the mid-air image and the half-mirror is 58° looking vertically downward from the eye position. (right)The viewing angle occupied by the left-right translation of the mid-air image is 35° in both directions.*

moving on stationary ground as the reference stimulus and a mid-air image moving in mid-air as the comparison stimulus. The hypothesis was as follows: The perceived speed of the mid-air image motion is greater when the ground moves in the opposite direction than in the same direction as the direction of the mid-air image motion.

4.1. Design of experimental setup

The experimental setup uses the EnchanTable proposed by Yamamoto et al., which can simultaneously display a mid-air image and a ground image in the same line of sight [YKKN15]. Figure 6 illustrates the optical design of the experimental setup. The experimental setup consisted of a display as a light source, a reflective surface, MMAP, louver film, and a half-mirror. The light emitted from the display passes through the MMAP and is then reflected by a half-mirror to form mid-air images. The louver film, which diffuses light rays traveling upward and transmits light rays traveling downward, was placed in front of the MMAP. This installation method transmits light that forms mid-air images and light that directly reaches the user's eye. The viewpoint was positioned 660mm horizontally from the mid-air image and fixed using a chin rest. The mid-air image was then moved on the display. The angle between the mid-air image and the viewpoint is shown in Figure 7.

We implemented an optical device to form a mid-air image, display the ground, and create a video image to be displayed using this device. The hardware consists of an LCD display LITEMAX SLD2126 (luminance $1600\,cd/m^2$) as the light source, a LCD monitor (Dell P2314T, 23 inch, $270\,cd/m^2$), an ASKA3D plate (488 mm × 488 mm) from ASKANET for the MMAP, MRH-001 for the half mirror (transmittance:30%, reflectance:40%), and W-0055 from Lintec for the louver film. Unity software Ver 2019.4.25f1 was used to create the images to be displayed.

4.2. Method

We recruited 19 participants (17 males and 2 female), ranging in age from 21 to 28, all of whom were students at the University of Electro-Communications. The sample size was 21 which is calculated using the G*Power 3.1 [FELB07] (One-way repeated-measures analysis of variance [ANOVA] with $f = 0.25$, $\alpha = 0.05$, and power of $1-\beta = 0.80$, with a correlation of 0.5 among repeated measures). The Ethical Review Committee of the University of Electro-Communications approved this study (ID#21064).

The experiment was conducted in a dark room using a mid-air image as the reference stimulus, a mid-air image as the comparison stimulus, and a random dot image as the ground image. Figure 8 shows an example of the presented stimuli. The mid-air image luminance measured from a viewing distance was $8.9\,cd/m^2$. A white circle 2.1 cm in diameter was used for the mid-air image. The speed of the mid-air image as the reference stimulus was 7.0 deg/s, and the ground moving under the mid-air image as the reference stimulus had five different velocities (60% faster than the mid-air image in the opposite direction, 30% faster than the mid-air image in the opposite direction, the same speed, and direction as the mid-air image, 30% faster than the mid-air image in the same direction, and 60% faster than the mid-air image in the same direction). The mid-air image moved from left to right, and when it reached the right edge, it reappeared from the left edge. Random dot images were used as the ground image, and the dots were evenly distributed such that one-fourth of the dots were white against the black ground. This random dot image was displayed across a display placed below the mid-air image. The actual size of the dot on the display was approximately 5 mm.

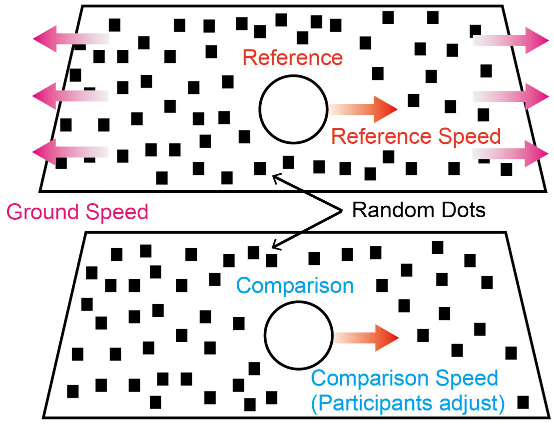

Figure 8: *The appearance of the mid-air image and the ground was displayed in the experiment. Participants estimated the speed of a reference stimulus over the moving ground and adjusted the speed of the comparison stimulus to equal the speed.*

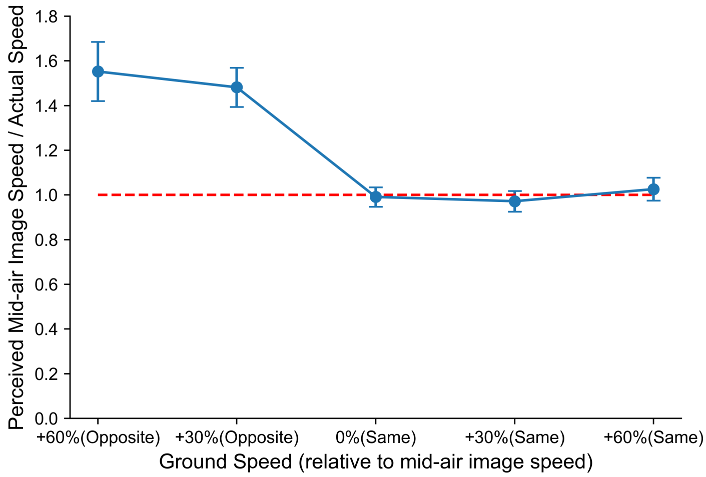

Figure 9: *Adjusted speed of the comparison stimulus for each condition. Error bars indicate standard error of the mean. The dotted line indicates the original speed of the mid-air image.*

Table 2: *Perceived Speed Pairwise Comparisons Significant at the 0.1% Level in all ground speed combinations*

Pairwise Comparison	p-value
60%(Opposite) vs 0%(Same)	p<0.001
60%(Opposite) vs 30%(Same)	p<0.001
60%(Opposite) vs 60%(Same)	p<0.001
30%(Opposite) vs 0%(Same)	p<0.001
30%(Opposite) vs 30%(Same)	p<0.001
30%(Opposite) vs 60%(Same)	p<0.001

In each trial, the participant first saw a reference stimulus moving over a scrolling background. The comparison stimulus was displayed after the reference stimulus disappeared, and the user had to adjust the speed of the comparison stimulus to match the speed of the reference stimulus. When the comparison stimulus was presented, the initial velocity of the comparison stimulus was 2.0 deg/s or 12.0 deg/s. The background was stationary when the comparison stimulus was presented. The speed of the comparison stimuli was adjusted using the up and down arrow keys on the keyboard, and the operation method was taught in advance. The adjustment range of the comparison stimulus speed was set at 0.07 deg/s. The display time for the reference stimulus was 10 seconds.

This procedure was repeated for a total of 20 trials, multiplying five different ground speeds by four repetitions (two ascending series and two descending series). The order of each trial presented was random for each participant in the experiment, and the duration of the experiment per participant was about 20 minutes.

4.3. Results

Figure 9 shows the average speeds of the comparison stimuli adjusted by each participant for each ground speed. A Shapiro-Wilk test indicated that the assumption of normality had been violated. Friedman's test was performed to analyze the differences between ground speeds concerning the adjusted speeds of the comparison stimuli, and statistically significant differences were found. ($\chi^2(4) = 56.36, p < 0.001$) Next, multiple comparison test was conducted using the Holm method. Table 2 shows the p-values for pairwise comparisons that are significant at the 0.1% level in all ground speed combinations.

4.4. Discussion

The experimental results showed that the perceived speeds when the ground moved in the opposite direction relative to the mid-air image were 58% higher than those when the ground moved in the same direction. Multiple comparisons (Table 2) showed significant differences when the ground was moved in opposite directions and when it was moved in the same direction. This result supports our hypothesis and is similar to those of previous studies (Loomis and Nakayama [NT78], Tynan and Sekuler [TS75], Walker and Powell [WP74]). The perceived speed did not vary significantly among the ground speed conditions in this experiment when the ground was moved in the opposite direction (5.5% change).

Another finding from the experiment is that when the ground moved in the same direction, the average perceived speed was comparable to the actual speed. This result differs from that of Tynan & Sekuler [TS75], who reported a reduction in perceived speed when the target and background move in the same direction.

5. General Discussion

In this study, a background was placed directly under a mid-air image to investigate whether changing the image on the background plane changes the perception of mid-air images. One concern with projecting images directly below the mid-air image is that the images and the mid-air image will overlap, reducing the visibility of the mid-air image. This problem can be addressed by erasing only the image overlapping the mid-air image, but this would require information on the observer's viewpoint and thus a more complex system. We intend to address this in the future.

The effect of the background surface created in this study on the perceptual change of the mid-air image may vary depending on the shape of the background surface where the image is displayed and the viewing environment. Due to the horizontal display area in this case, it is unclear whether the same effect could be achieved even if the display area had a complex shape. The viewing environment in this experiment was a dark room, and the subjects focused on the mid-air image and the image displayed below the mid-air image. However, it is unclear whether the same results as in the present experiment can be obtained when something objects other than the mid-air image and the image displayed below the mid-air image is in view.

6. Conclusion

In this study, we showed that the apparent depth of a mid-air image can be changed by projecting a shadow directly below the mid-air image and changing the length of the shadow (Experiment 1). In experiment 2, we found that by moving the image displayed below the moving mid-air image in the opposite direction of the moving mid-air image, the apparent speed of motion of the mid-air image could be increased. In Experiment 1, three different elliptical shadows were prepared for a mid-air image in the shape of a sphere with a diameter of 5 cm in the horizontal direction and different lengths in the depth direction. The results of Experiment 1 showed that as the depth of the shadow increases (or decreases), the perceived depth of the mid-air image that matches it also increases (or decreases). In Experiment 2, the participants watched a mid-air image moving from left to right at a velocity of 7.0 deg/s and the ground, which moved in five different conditions. The conditions were 60% faster than the mid-air image in the opposite direction, 30% faster than the mid-air image in the opposite direction, the same speed and direction as the mid-air image, 30% was faster than the mid-air image in the same direction, and 60% faster than the mid-air image in the same direction. Psychophysical experiments showed that the perceived speed of the mid-air image when the ground moved in the opposite direction of the mid-air image movement was 58% faster than the perceived speed when the ground moved in the same direction.

We believe that the ground created in this study supports the design of content that uses mid-air images because it can easily extend the range of depth and speed perception of mid-air images. In the future, in addition to further pursuing the design of the ground created in this study, we would like to study the creation and evaluation of ground that changes perceptual characteristics other than depth and speed.

Acknowledgments

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References

[CRG86] CARELLO C., ROSENBLUM L., GROSOFSKY A.: Static depiction of movement. *Perception 15*, 1 (1986), 41–58. 1

[CV95] CUTTING J. E., VISHTON P. M.: Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth. In *Perception of space and motion*. Elsevier, 1995, pp. 69–117. 3

[FELB07] FAUL F., ERDFELDER E., LANG A.-G., BUCHNER A.: G* power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods 39*, 2 (2007), 175–191. 5

[HL94] HSU S. C., LEE I. H.: Drawing and animation using skeletal strokes. In *Proceedings of the 21st annual conference on Computer graphics and interactive techniques* (1994), pp. 109–118. 1

[Kaw19] KAWABE T.: Shadow-based illusion of depth and transparency in printed images. *ACM Transactions on Applied Perception (TAP) 16*, 2 (2019), 1–12. 2

[KKMB96] KERSTEN D., KNILL D. C., MAMASSIAN P., BÜLTHOFF I.: Illusory motion from shadows. 2

[KM08] KAWABE T., MIURA K.: New motion illusion caused by pictorial motion lines. *Experimental Psychology 55*, 4 (2008), 228–234. URL: https://doi.org/10.1027/1618-3169.55.4.228, doi:10.1027/1618-3169.55.4.228. 1

[KM14] KERSTEN D. J., MAMASSIAN P.: Cast shadow illusions. 2, 4

[KO18] KOIKE T., ONISHI Y.: Aerial 3d imaging by retroreflective mirror array. In *Proceedings of the 2018 ACM Companion International Conference on Interactive Surfaces and Spaces* (New York, NY, USA, 2018), ISS '18 Companion, Association for Computing Machinery, p. 25–29. URL: https://doi.org/10.1145/3280295.3281365, doi:10.1145/3280295.3281365. 2

[KTY*14] KIM H., TAKAHASHI I., YAMAMOTO H., MAEKAWA S., NAEMURA T.: Mario: Mid-air augmented reality interaction with objects. *Entertainment Computing 5*, 4 (2014), 233–241. 1, 2

[LN73] LOOMIS J., NAKAYAMA K.: A velocity analogue of brightness contrast. *Perception 2*, 4 (1973), 425–428. 2

[MNM06] MAEKAWA S., NITTA K., MATOBA O.: Transmissive optical imaging device with micromirror array. In *Three-dimensional TV, video, and display V* (2006), vol. 6392, International Society for Optics and Photonics, p. 63920E. 2

[NNTL96] NORMAN H. F., NORMAN J. F., TODD J. T., LINDSEY D. T.: Spatial interactions in perceived speed. *Perception 25*, 7 (1996), 815–830. 1, 2

[NT78] NAKAYAMA K., TYLER C. W.: Relative motion induced between stationary lines. *Vision research 18*, 12 (1978), 1663–1668. 6

[Ots14] OTSUBO M.: Optical imaging apparatus and optical imaging method using the same, Apr. 22 2014. US Patent 8,702,252. 2

[SKT03] SUGANO N., KATO H., TACHIBANA K.: The effects of shadow representation of virtual objects in augmented reality. In *The Second IEEE and ACM International Symposium on Mixed and Augmented Reality, 2003. Proceedings.* (2003), IEEE, pp. 76–83. 2

[TS75] TYNAN P., SEKULER R.: Simultaneous motion contrast: Velocity, sensitivity and depth response. *Vision research* (1975). 1, 2, 6

[Wan92] WANGER L.: The effect of shadow quality on the perception of spatial relationships in computer generated imagery. In *Proceedings of the 1992 Symposium on Interactive 3D Graphics* (New York, NY, USA, 1992), I3D '92, Association for Computing Machinery, pp. 39–42. URL: https://doi.org/10.1145/147156.147161, doi:10.1145/147156.147161. 2, 4

[WP74] WALKER P., POWELL D. J.: Lateral interaction between neural channels sensitive to velocity in the human visual system. *Nature 252*, 5485 (Dec. 1974), 732–733. URL: https://doi.org/10.1038/252732a0, doi:10.1038/252732a0. 2, 6

[YKKN15] YAMAMOTO H., KAJITA H., KOIZUMI N., NAEMURA T.: Enchantable: Displaying a vertically standing mid-air image on a table surface using reflection. In *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces* (2015), pp. 397–400. 5

[YYA*14] YAMAMOTO H., YASUI M., ALVISSALIM M. S., TAKAHASHI M., TOMIYAMA Y., SUYAMA S., ISHIKAWA M.: Floating display screen formed by airr (aerial imaging by retro-reflection) for interaction in 3d space. In *2014 International Conference on 3D Imaging (IC3D)* (2014), pp. 1–5. doi:10.1109/IC3D.2014.7032590. 2

[ZFVDH00] ZHOU H., FRIEDMAN H. S., VON DER HEYDT R.: Coding of border ownership in monkey visual cortex. *Journal of Neuroscience 20*, 17 (2000), 6594–6611. 1