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A variant of the anomalous motion illusion based upon contrast and visual latency

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Abstract. We examined a variant of the anomalous motion illusion. In a series of experiments, we ascertained luminance contrast to be the critical factor. Low-contrast random dots showed longer latency than high-contrast ones, irrespective of whether they were dark or light (experiments 1 – 3). We conjecture that this illusion may share the same mechanism with the Hess effect, which is characterised by visual delay of a low-contrast, dark stimulus in a moving situation. Since the Hess effect is known as the monocular version of the Pulfrich effect, we examined whether illusory motion in depth could be observed if a high-contrast pattern was projected to one eye and the same pattern of low-contrast was presented to the other eye, and they were binocularly fused and swayed horizontally. Observers then reported illusory motion in depth when the low-contrast pattern was dark, but they did not when it was bright (experiment 4). Possible explanations of this inconsistency are discussed.

1 Introduction

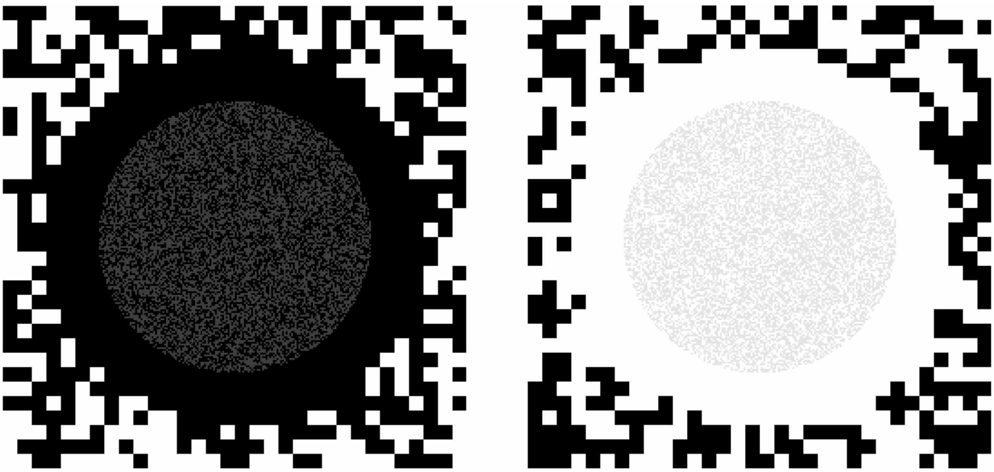
Integration of local motion signals into global motion perception has been studied from a variety of viewpoints (eg Williams and Sekuler 1984; Wilson 1994); this has brought out several unsolved problems. In particular, of recent interest is the anomalous motion illusion in which part of a stationary image appears to move while the rest appears to be stationary. Variations of anomalous motion illusion have dramatically multiplied during the past decade (see Kitaoka 2005; Pinna and Spillmann 2005).

In the present study, we demonstrate a novel variant in which an inset made up of low-contrast random dots appears to move when surrounded by high-contrast random dots (figure 1a). When observers move this figure laterally, the inset disk appears to lag behind the surround. When observers rotate this figure, apparent rotation of the inset is observed, lagging behind that of the surround. If observers approach or move away from the figure with their eyes fixed at the centre of the image, apparent expansion or contraction of the inset is observed which lags behind that of the surround.

1.1 *A review of anomalous motion illusions*

Before we describe our experimental study, let us summarise variants of anomalous motion illusions that have been reported so far (table 1). There can be several ways of classifying many illusions, but we propose one based on phenomenology. First, some illusions can be perceived without much effort ('automatic' type), while others require retinal-image motion due to either eye or stimulus motion ('motion-dependent' type). The motion-dependent type itself splits into two groups. One is characterised by illusory motion the direction of which is different from the retinal-image motion (group I), while the other is characterised by illusory motion the direction of which is parallel to the retinal-image motion (group II).

1.1.1 *'Automatic' type.* Op art, which is characterised by periodic high-spatial-frequency black-and-white patterns and gives a vivid dynamic impression, can also be a variant of anomalous motion illusion. The examined images of Op art include MacKay's (1957)



(a) (b)

Figure 1. A new variant of the anomalous motion illusion depending on the difference in contrast between two regions. The low-contrast inset appears to move relative to the high-contrast surround in the same direction as that of retinal-image motion when the image is swayed. (a) The inset consists of black and dark-gray random dots while the surround is made up of black and white random dots. (b) The inset consists of white and light-gray random dots while the surround is made up of black and white random dots. The illusion of (a) appears to be stronger than that of (b). Moreover, for both images, the illusion appears to be stronger when seen in the peripheral vision than when seen in the central vision.

Table 1. Classification of anomalous motion illusions.

I 'Automatic' type
- 1.1 Illusory motion observed in Op art
  - MacKay's 'ray' pattern (MacKay 1957)
  - *Enigma* painting (Leviant 1996)
  - Bridget Riley's *Fall* (Zanker et al 2003)
- 1.2 Illusory motion observed well in the peripheral vision
  - Fraser – Wilcox illusion (Fraser and Wilcox 1979)
  - Peripheral drift illusion (Faubert and Herbert 1999)
  - 'Optimised' Fraser – Wilcox illusion (Kitaoka and Ashida 2003)[a]
- 1.3 Illusory motion observed well in the central vision
  - Central drift illusion (Kitaoka and Ashida 2004)

2 'Motion-dependent' type[b]
- 2.1 Illusory motion in a direction different from the retinal-image motion
  - Ouchi illusion (Spillmann et al 1986)
  - Hine illusion (Hine et al 1995)
  - Oblique-line illusion (Bressan and Vezzani 1995)
  - Pinna – Brelstaff illusion (Pinna and Brelstaff 2000)
  - 'Optimised' Pinna – Brelstaff illusion (Gurnsey et al 2002)
  - Petrov – Popple illusion (Petrov and Popple 2002)
  - Illusion of Y-junctions (Kitaoka 2005)[c]
- 2.2 Illusory motion in the direction parallel to the retinal-image motion
  - Fluttering-heart illusion (Helmholtz 1867/1962)
  - Swinging-motion illusion (Khang and Essock 2000)
  - Floating-motion illusion (Pinna and Spillmann 2002)
  - Contrast-dependent visual-delay illusion (the present study)

[a] Backus and Oruç (2005) named this the RAP (repeated asymmetric patterns) illusion.
[b] Pinna and Spillmann (2005) labelled this category the sliding-motion illusion.
[c] Images are also exhibited in http://www.psy.ritsumei.ac.jp/~akitaoka/Yjunctione.html.

'ray' pattern, the *Enigma* painting (Leviant 1996), or Bridget Riley's *Fall* (Zanker et al 2003). Gregory (1993) regarded involuntary accommodative oscillations as a possible source of the illusion, while Kumar and Glaser (2006) suggested that it has a cortical origin. Zanker (2004) pointed out the critical role of involuntary eye movements and explained this with a computational model. For other recent studies see Fermüller et al (1997), Zanker and Walker (2004), or Gori et al (2006). In relation to Op art, Wade (1977) reported that prolonged observation of a stationary grating gives a waving, oscillating, or scintillating appearance. He suggested that scintillation might be produced by small involuntary eye movements.

Fraser and Wilcox (1979) proposed a variant of the anomalous motion illusion where circles made up of repeated pie slices filled with triangular luminance profiles appear to rotate 'automatically'. This illusion (Fraser – Wilcox illusion) is more vivid in peripheral vision than in central vision (Fraser and Wilcox 1979; Faubert and Herbert 1999; Naor-Raz and Sekuler 2000). Faubert and Herbert (1999) claimed that this illusion is triggered by eye movements or blinks, and regarded the Fraser – Wilcox illusion as being the same phenomenon as the blink-dependent motion illusion that they discovered and called 'peripheral drift illusion'. They explained that this illusory motion might be caused by the difference in visual latency between dark and bright parts in luminance gradients. Naor-Raz and Sekuler (2000) revealed that the illusion magnitude is a positive, nearly linear function of contrast. They ruled out fluctuations of accommodation as a possible source.

Kitaoka and Ashida (2003) optimised the Fraser – Wilcox illusion to give a much more powerful motion illusion by proposing a rule that illusory motion is strong in the repetition of the basic arrangement as follows: black → dark-gray → white → light-gray → black. For a recent classification of the optimised Fraser – Wilcox illusion see Kitaoka (2006). Conway et al (2005) explained this illusion in terms of contrast-dependent response timing differences and regarded it as a static version of four-stroke apparent motion (Anstis and Rogers 1986; Mather and Murdoch 1999). Backus and Oruç (2005) also explained this illusion in terms of contrast-dependent response timing differences, while they also took into account the process of adaptation to luminance. Murakami et al (2006) stressed the role of fixational eye movement in this illusion and explained it with the gradient model.

Kitaoka and Ashida (2004) proposed a new variant that resembles the optimised Fraser – Wilcox illusion and they called it the 'central drift' illusion because this illusion is observed in the fovea as well as in the visual periphery. The direction of illusory motion is from the low-contrast part to the high-contrast part along a luminance gradient. This direction is a reversal of the illusory motion of the optimised Fraser – Wilcox illusion. No explanation has ever been given to this illusion.

1.1.2 *'Motion-dependent' type, group I.* A typical anomalous motion illusion is the Ouchi illusion, which was discovered by Spillmann et al (1986) in a design book written by Ouchi (1977). It seems that Ouchi accidentally produced this illusion design and was not aware of the motion illusion because he did not exhibit any other images that included anomalous motion illusion. Many reports suggest that this illusion is based upon a failure in two-dimensional integration of motion signals (Hine et al 1995, 1997; Fermüller et al 2000; Mather 2000; Ashida 2002; Ashida et al 2005; Pinna and Spillmann 2005).

Hine et al (1995, 1997) examined images which consisted of two gratings of different orientations that were assumed to represent low-spatial-frequency components of the Ouchi image. They also suggested that this illusion is generated by a failure in two-dimensional integration of motion signals. Recently, the Hine illusion was examined in a different configuration by Gori and Hamburger (2006), who called it the

Rotating-Tilted-Lines illusion. Bressan and Vezzani (1995) proposed a similar illusion using simple line segments and related their illusion to the aperture problem.

Khang and Essock (1997a, 1997b) examined the effects of several factors on the Ouchi illusion. They suggested that the Ouchi illusion might have a common cause with their swinging-motion illusion (Khang and Essock 2000), which they explained on the basis of visual delay in the gain-setting mechanisms between the ON and OFF pathways.

Pinna and Brelstaff (2000) proposed a new variant of the anomalous motion illusion in which each element consisted of two black line segments and two white ones drawn on a gray background. Gurnsey et al (2002) proposed an 'optimised' version of the Pinna–Brelstaff illusion, in which the elements were tilted Gabor patches (also see Gurnsey and Pagé 2006). Ichikawa et al (2006) stressed the role of oblique components in this illusion, too.

Kitaoka (2005) proposed a variant of the anomalous motion illusion called the illusion of 'Y-junctions', which was originally presented as a tilt illusion (Kitaoka et al 2001). No explanation has ever been given for this illusion.

Petrov and Popple (2002) proposed a novel variant, which is accompanied by, or depends on, apparent brightness changes. They explained their illusion in terms of the effect of negative afterimages.

1.1.3 *'Motion-dependent' type, group II.* Pinna and Spillmann (2002) proposed a variant called the floating-motion illusion, in which the direction of illusory motion is parallel to the retinal-image motion. They suggested that different speed signals may contribute to this illusion. It has been reported that the perceived speed of a stimulus depends on contrast (Thompson 1982; Cavanagh et al 1984; Stone and Thompson 1992; Gegenfurtner and Hawken 1996; Blakemore and Snowden 1999; Anstis 2001, 2004) or spatial frequency (Diener et al 1976; Campbell and Maffei 1981; Smith and Edgar 1990), but no one had proposed an anomalous motion illusion based upon differences in perceived speeds before Pinna and Spillmann (2002).

The fluttering-heart illusion, an anomalous motion of a vividly coloured pattern on a sheet of a different colour (the combination of red and blue is preferred), has been known for a long time (von Helmholtz 1867/1962). This illusion has been thought to depend on the difference in visual latency between different colours (von Kries 1896; von Grünau 1975a, 1975b, 1976). But more recently, it has been considered that the illusion reflects a difference in visual latency between chromatic and achromatic borders (Nguyen-Tri and Faubert 2003) or a difference in the perceived speed between the two areas (Arnold and Johnston 2003).

Our anomalous motion illusion (figure 1) should be placed in this group ('motion-dependent' type, group II).

1.2 *Our illusion and the Hess effect*

Our anomalous motion illusion shares many properties with the Hess effect (Hess 1904; Howard and Rogers 1995), a phenomenon in which a darker bar appears to lag behind a brighter one when observers see two moving bars that are physically aligned but are different in luminance. This phenomenon is explained in terms of visual delay of the former compared with the latter. It was also regarded as the monocular counterpart of the Pulfrich effect, in which low luminance has been believed to cause longer visual latency (Pulfrich 1922; Lit 1949; Julesz and White 1969; Rogers and Anstis 1972).

Both our illusion and the Hess effect can be explained if a low-contrast region gives longer visual latency than a high-contrast one. But since Hess and following studies (Guth 1964; Prestrude and Baker 1968; Wilson and Anstis 1969; Prestrude 1971; Williams and Lit 1983) compared stimuli of different luminance only against a dark background, the role of contrast in visual latency remained unclear. The reason for this incompleteness might stem from the belief that the Hess effect provides evidence that stimulus intensity determines visual latency, though Williams and Lit (1983) did not support the idea that the Hess effect is caused by an intensity-dependent retinal response. This low-luminance hypothesis predicts longer latency for darker stimuli even if the background is of high luminance. Wilson and Anstis (1969) mentioned that they confirmed this expectation in a preliminary work.

The effect of contrast was also mentioned for the Pulfrich effect by Dodwell et al (1968) and for the Hess effect by Prestrude and Baker (1971). The former suggested the involvement of contrast but did not produce clear evidence. The latter did not obtain positive evidence and the space-average luminance level was thought to account for this effect. It therefore remains unclear whether the crucial property is the intensity (luminance) or luminance contrast.

Yet, our anomalous motion illusion shows that the inset of low contrast but of high luminance also appears to lag behind the surround (of high contrast) on a white background (figure 1b). Moreover, a recent neurophysiological study revealed the existence of visual neurons in V1 or MT that respond faster to high-contrast stimuli than low-contrast ones (Conway et al 2005)

1.3 *Purpose of this study*

Our variant of illusion has an advantage in that the effect is so strong that the illusion is seen very clearly even under normal viewing conditions. Although we admit that different factors work in different stimulus configurations, understanding the critical factors of our variant will provide insights into other illusions as we described above.

There are two outstanding questions to be answered, as is evident from the review above: (i) whether the illusory motion depends on luminance (intensity) per se or its contrast, and (ii) whether the illusion depends on visual latency or perceived speed. Moreover, it is of interest to examine how contrast affects the Pulfrich effect. We thus examined the effects of visual latency in experiment 1, perceived speed in experiment 2, both in experiment 3, and the Pulfrich stereoscopic effect in experiment 4.

2 Experiment 1

To examine the role of contrast in visual latency, we produced a stimulus that consisted of three rows of random dots, two giving high contrast and one giving low contrast. The stimulus swayed sinusoidally in the horizontal direction, and the temporal phases between the high-contrast and low-contrast rows were manipulated. Subject's task was to match their apparent temporal phases.

2.1 *Methods*

2.1.1 *Subjects.* Two naive subjects and the two authors participated. All subjects had normal or corrected-to-normal acuity.

2.1.2 *Apparatus.* Stimuli were produced with DirectX on Windows 98 and displayed on a CRT monitor (Sony GDM-F400) placed in a dark room. The screen resolution was 1024×768 pixels and the refresh rate was 120 Hz.

2.1.3 *Stimuli.* The stimuli were three rows of random dots with a black (0.29 cd m^{-2}: the lowest luminance) or white (125 cd m^{-2}: the highest luminance) background (figures 2a and 2b, respectively). Both the upper and lower rows consisted of black and white random dots (space-average: 57 cd m^{-2}) while the middle row was made up of black and gray ones (figure 2a) or white and gray ones (figure 2b). The luminance of the gray dots was systematically changed; the space-average luminance of the middle row was 0.85, 12.93, 24.16, 35.39, 46.62, and 57.00 cd m^{-2} for the black-background stimulus (light-on-dark); and 57, 69, 81, 93, 104, and 117 cd m^{-2} for the white-background

(a)

(b)

Figure 2. Test stimuli for experiments 1 – 3. (a) Stimuli with a black background (the lowest luminance). (b) Stimuli with a white background (the highest luminance). For each panel, the upper and lower rows consisted of random dots of the highest or lowest luminance on the lowest-luminance or highest-luminance background, respectively. On the other hand, the middle row consisted of gray random dots of variable luminance on a dark or light background. During the test period, stimuli swayed horizontally in a sinusoidal fashion, with the red fixation cross being stationary.

stimulus (dark-on-light). When the space-average luminance of the middle row was 57 cd m^{-2}, it was made up of black and white random dots.

The dot size was 1.07 min of arc × 1.07 min of arc. Both the upper and lower rows were 1.94 deg (height) × 14.38 deg (length), while the middle row was 0.44 deg (height) × 13.13 deg (length). The gap between the upper row and the middle one, and the gap between the lower row and the middle one, was 0.72 deg in each case.

During the test periods, the upper and lower rows coherently swayed in the horizontal direction, the path being sinusoidal. The temporal frequency was 2 Hz and the amplitude was 0.5 deg (ie the swaying distance was 1.0 deg). Although the middle row also swayed in the same manner, the temporal phase was changeable. A small red cross was superimposed on the middle row as a fixation point.

2.1.4 *Procedure.* Subjects were individually tested. Their heads were fixed with a head-and-chin rest. They observed the stimuli through natural pupils, the viewing distance being 60.5 cm. First, the fixation point appeared. A trial started when subjects fixed their eyes on the fixation point and pushed the start key: the stimuli then appeared and started to move. The subject's task was to adjust the temporal phase of the middle row to match that of the upper and lower rows as close as possible. In other words, they minimised the perceived relative motion between the rows. They were instructed not to rely on their judgments of the left and right edges but that of the central area. The phase difference was changed in ± 2.1 ms steps by subject's operation of pressing either of two keys. Such sub-frame accuracy was possible for the sinusoidal sway as analogous to the spatial sub-pixel coding of sinusoidal gratings. The initial phase for each trial was randomly set. After the subjects matched the phase, both the stimulus and the fixation point disappeared.

Stimuli with a black and with a white background were tested in separate sessions, each of which included 6 trials (= 6 conditions of luminance or contrast of the middle row) tested in random order. Ten sessions were conducted for each background. Patterns of random dots were changed for each trial.

2.2 *Results and discussion*

Figure 3 shows the estimated temporal delays for the middle row (low-contrast row) plotted as a function of the space-average luminance. On the black background, the phase temporal delay for the middle row was about 25 ms behind the upper and lower ones (high-contrast rows) when the space-average luminance of the middle row was 0.85 cd m^{-2}, which dramatically decreased as the space-average luminance of the middle row increased ($F_{5,15} = 45.77$, $p < 0.01$) (figure 3a). This result is consistent with Prestrude and Baker (1968), who reported delays between 4.3 and 39.4 ms. On the white background, the phase delay for the middle row was about 13 ms behind the upper and lower ones when the luminance of the middle row was high, and decreased as the space-average luminance decreased ($F_{5,15} = 23.37$, $p < 0.01$) (figure 3b). To sum up, the phase delay was longer when the pattern luminance was closer to the background, that is, the lower the contrast the longer the visual latency.

This visual-delay illusion thus chiefly depends on contrast, not on luminance. This result disagrees with the idea that the Hess effect depends mainly on luminance

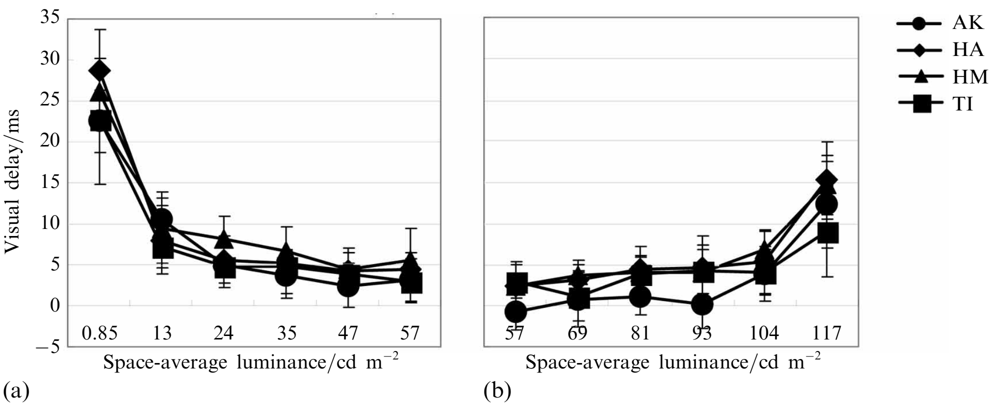


Figure 3. The results of experiment 1. Measured temporal delays of the middle row plotted as a function of the space-average luminance. (a) In the black-background condition (0.29 cd m^{-2}), the visual delay of the middle row relative to the upper and lower rows was long when the space-average luminance of the middle row was *low* (or of low contrast). (b) In the white-background condition (125 cd m^{-2}), the visual delay of the middle row was long when its space-average luminance was *high* (or of low contrast).

(Wilson and Anstis 1969). Actually, absolute luminance had some effects on this illusion because the black-background figures gave longer delays than the white background ones as shown in figure 3. This difference, however, might be due to the difference in adaptation levels (Lythgoe 1938; Standing et al 1968).

3 Experiment 2

The results of experiment 1 indicate that the visual-delay illusion depends on the longer visual latency for low-contrast patterns. However, the difference in perceived speed between high-contrast and low-contrast patterns (Thompson 1982; Stone and Thompson 1992) might possibly contribute to this type of motion illusion. We then examined whether the difference in perceived speed is involved or not.

3.1 *Methods*

3.1.1 *Subjects.* The same two naive subjects and the two authors participated.

3.1.2 *Apparatus.* The apparatus was the same as in experiment 1.

3.1.3 *Stimuli.* The stimuli were the same as in experiment 1, except that the temporal phases of sway were synchronised between the middle row and the flanks, while the swaying amplitude of the middle row was manipulated. This operation effectively varied the speed of the middle row while the temporal frequency of the sway remained the same.

3.1.4 *Procedure.* Subject's task was to adjust the apparent maximum speed of the middle row to that of the upper and lower rows. The speed was controlled by changing the amplitude of sway of the middle row in 0.5% steps. The subjects were instructed not to rely on their judgments of the swaying distance of the left and right edges, but to concentrate on the speed in the centre. The other conditions were the same as in experiment 1.

3.2 *Results and discussion*

The estimated perceived speed of the middle row is plotted as a function of the space-average luminance in figure 4. Note that an estimated speed of more than 100% implies that the subject needed to lower the speed of the middle row to match the perceived speeds.

There are some individual differences. One subject (TI) did not show any consistent change in perceived speed as a function of luminance. This might have been caused

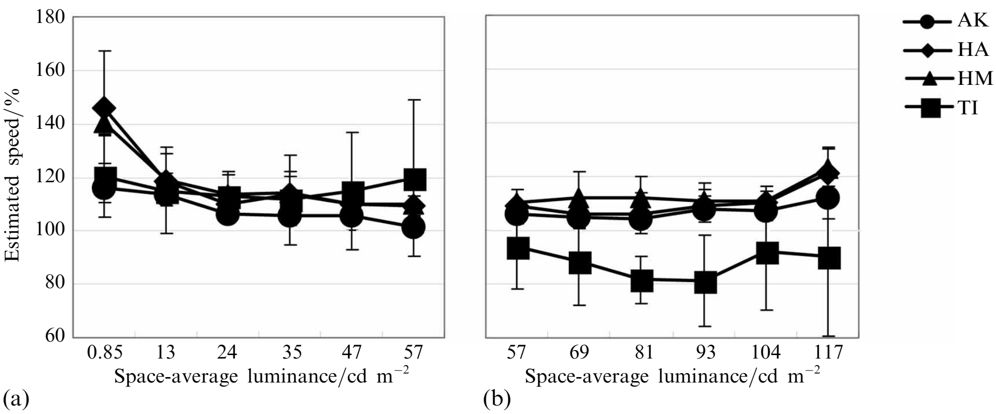


Figure 4. The results of experiment 2. Estimated perceived speed of the middle row plotted as a function of the space-average luminance. (a) In the black-background condition (0.29 cd m^{-2}), the perceived speed of the middle row was faster than that of the upper and lower rows when the average luminance of the former was low. One subject (TI) did not show this tendency. (b) In the white-background condition (125 cd m^{-2}), the perceived speed of the middle row tended to be faster than that of the flanks when its average luminance was high. One subject (TI) did not show this tendency.

by the difficulty in performing this task as we shall mention later. For the other three subjects, on the black background the perceived speed of the middle row was faster than that of the upper and lower ones when the space-average luminance of the middle row was low (0.85 cd m^{-2}), and decreased as the luminance of the middle row increased ($F_{5,10} = 7.69$, $p < 0.01$) (figure 4a). On the white background, for these three subjects, the perceived speed of the middle row was slightly faster than that of the flanks when the middle row was made up of white and nearly white (117 cd m^{-2}) random-dot background, and decreased as the luminance of the middle row decreased ($F_{5,10} = 8.06$, $p < 0.01$) (figure 4b).

These results show a slight tendency that the lower the contrast the faster the perceived speed (for the three subjects). This characteristic may also contribute to the visual-delay illusion, but the faster perceived speed for the lower-contrast region does not account for its perceptual lag. It should also be noted that all the subjects found it impossible to completely match the perceived motion of all three rows because the middle row was never well synchronised with the other two rows. It did not seem that the phase delay could be compensated by adjusting the speed.

Moreover, this result disagrees with the general observation that the lower the contrast the slower the perceived speed (Thompson 1982; Cavanagh et al 1984; Stone and Thompson 1992; Blakemore and Snowden 1999; Anstis 2001, 2004). But their observation was obtained when the speed of the grating was relatively slow (1–8 Hz of a 2 cycles deg^{-1} grating = 0.5–4 deg s^{-1}), whereas the reversal was found when the speed was high (16 Hz of a 2 cycles deg^{-1} grating = 8 deg s^{-1}) (Thompson 1982). The maximum speed of our stimuli was relatively high (6.28 deg s^{-1}), which was probably higher than the speed of Thompson's reversal point. Although direct comparison is not possible because of very different types of stimuli (gratings versus random dots; translation versus oscillation), our results do not necessarily contradict the earlier reports.

4 Experiment 3

Although experiments 1 and 2 revealed an involvement of visual delay and perceived speed in the present motion illusion, we were concerned that the two factors might have had some crosstalk with each other. In fact, in experiment 2 one subject reported severe difficulty with adjusting the speed because of apparent phase asynchrony. In the present experiment, subjects freely adjusted both the phase and speed within each trial.

4.1 *Methods*

4.1.1 *Subjects.* The two authors participated.

4.1.2 *Apparatus.* The apparatus was the same as in experiments 1 and 2.

4.1.3 *Stimuli.* The stimuli were the black-background ones, which were the same as in experiments 1 and 2, except that the phase delay and the amplitude could be independently controlled.

4.1.4 *Procedure.* Subject's task was to adjust the temporal phase and the perceived speed of the middle row to match those of the upper and lower rows in each trial. Four adjustment keys were used, two for the temporal phase and the other two for the perceived speed. The other conditions were the same as in experiments 1 and 2.

4.2 *Results and discussion*

The results (figure 5) were similar to those in experiments 1 and 2 (figures 3 and 4). These results support the idea that the lower the contrast the longer the visual latency, and the lower the contrast the faster the perceived speed. However, the results suggest that the contrast has a much stronger effect on visual latency than on perceived speed.

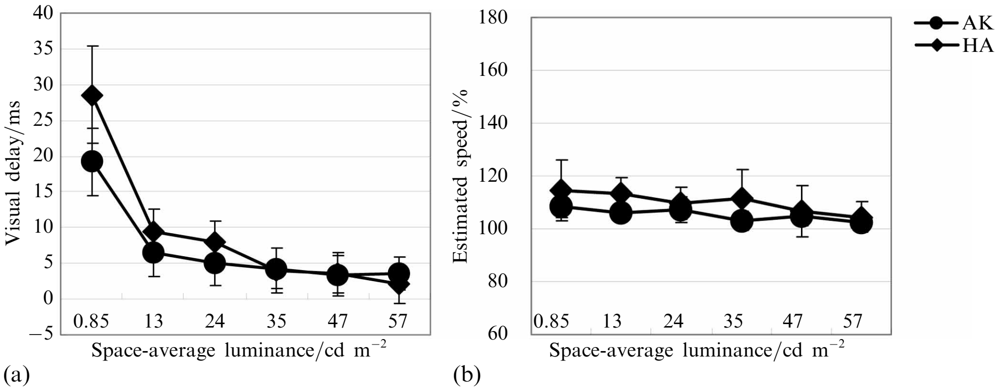


Figure 5. The results of experiment 3. Only the black-background condition (0.29 cd m^{-2}) was tested. (a) The middle row gave longer visual delay than the upper and lower rows when the space-average luminance of the former was low. (b) The middle row gave slightly faster perceived speed than the flanks when the space-average luminance of the former was low. These results agreed with experiments 1 and 2.

5 Experiment 4

When a bar of high luminance and a bar of low luminance are projected to each eye, and both images are binocularly fused and swayed horizontally, observers see an illusory motion in depth. This stereoscopic phenomenon is known as the Pulfrich effect (Rogers and Anstis 1972; Howard and Rogers 1995). The accepted explanation of the Pulfrich effect is based upon the binocular difference in luminance; and with the dark stimulus having a longer latency than the light one, this yields their positional displacement between the two eyes. This explanation differs from our contrast account. It is therefore of interest to check whether illusory motion in depth, like the Pulfrich effect, is observed not only in a dark-background condition but also in a bright-background condition.

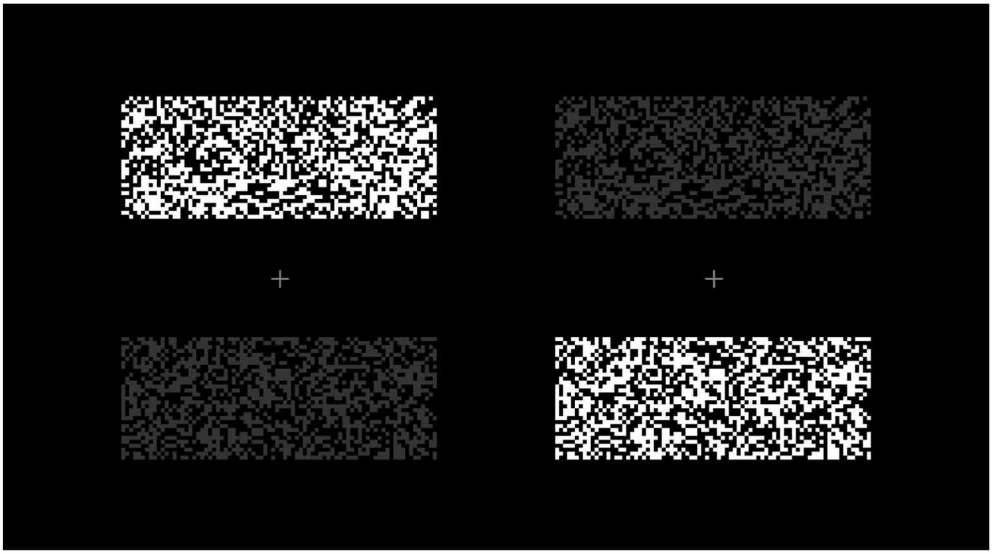
5.1 *Methods*

5.1.1 *Subjects.* The two authors, one of the two naive subjects in experiments 1 and 2 (HM), and another naive subject (TS) participated. All subjects were experts in stereoscopic fusion and had corrected-to-normal acuity.

5.1.2 *Apparatus.* The apparatus was the same as in experiment 1.

5.1.3 *Stimuli.* The stimuli were stereograms as shown in figure 6. In the black-background case (figure 6a), a black-and-white (57 cd m^{-2}) random-dot block and a black-and-gray one (0.85, 12.93, 24.16, 35.39, 46.62, and 57.00 cd m^{-2}) were paired for each eye. In the white-background case (figure 6b), a black-and-white (57 cd m^{-2}) random-dot block and a white-and-gray one (57, 69, 81, 93, 104, and 117 cd m^{-2}) were paired for each eye. The dot size was 1.07 min of arc $\times$ 1.07 min of arc. The size of a block was 1.88 deg (height) $\times$ 5.00 deg (length). The gap between the upper blocks and the lower ones, and the gap between the right blocks and the left ones, were both 1.88 deg. The upper-left and lower-right blocks were of high contrast while the upper-right and lower-left blocks were of low contrast. Fixation points (small red crosses) were placed in the gap between the upper and lower blocks. These fixation points had no binocular disparity relative to the left and right blocks. The other conditions were the same as in experiment 1.

5.1.4 *Procedure.* After subjects binocularly free-fused the right and left fixation points, they pushed the start key: the stimulus then appeared and started to move horizontally in the same sinusoidal fashion as experiments 1 – 3. During tests, subjects fixed their eyes



(a)

(b)

Figure 6. Test stimuli for experiment 4. These were stereograms, in which observers cross-fused the left and right random-dot blocks. (a) Stimuli in a black background. (b) Stimuli in a white background. A block for one eye consisted of random dots of the highest or lowest luminance on a lowest-luminance or highest-luminance background (= the high-contrast block), while the other block for the other eye consisted of the same random dots but variable luminance (= low-contrast blocks). During the test, stimuli swayed horizontally in a sinusoidal fashion, with the red fixation crosses being stationary.

on the fixation points. Their task was to report whether or not they saw an illusory motion in depth by comparing the depths between the upper and lower blocks. There were no time limits and the subjects reported the appearance by pressing a key. Fifteen trials were conducted for each background in random order.

5.2 *Results and discussion*

When random dots of high contrast and those of low contrast were fused, illusory motion in depth was frequently observed in the black-background stereograms (figure 7a) but not in the white-background ones (figure 7b). The former corresponds to the Pulfrich

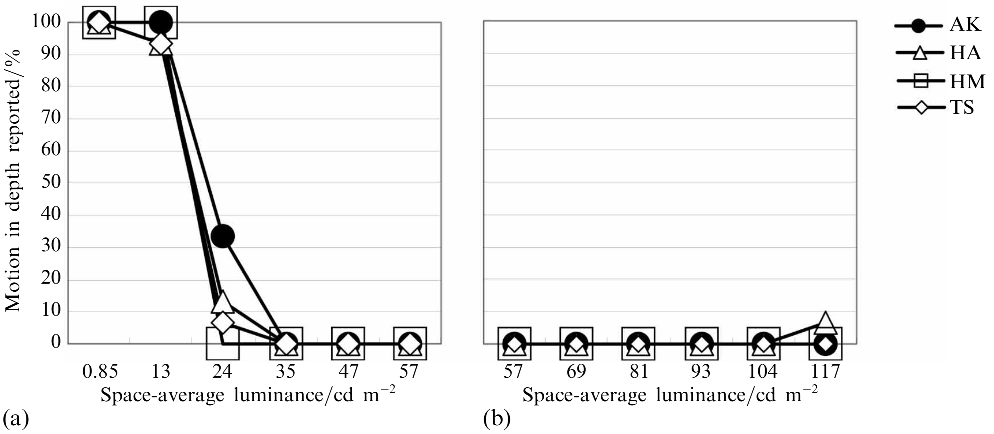


Figure 7. The results of experiment 4. (a) In the black-background condition (0.29 cd m^{-2}), the apparent motion in depth (or the Pulfrich effect) was frequently observed when the space-average luminance of the low-contrast block was *low*. (b) In the white-background condition (125 cd m^{-2}), such apparent motion in depth was hardly observed in each condition.

effect, whereas the latter does not. It appears to be difficult for any model based upon visual latency to explain this asymmetry.

One may point out a possibility that the difference in visual latency in the white-background stimuli was too small to generate illusory motion in depth. But this is not the case, since the measured delay of the white-background stimulus of 117 cd m^{-2} was longer than that of the black-background stimulus of 12.93 cd m^{-2} (figure 3a). The latter, when fused with the black-and-white block, nearly always gave the illusory motion in depth (figure 7a).

There is a possibility that this difference is due to the failure of binocular fusion (ie to binocular rivalry) between a white and nearly-white block and a black-and-white one, since the subjects sometimes reported difficulty of stable fusion in such a stereogram. This possibility is supported by a preliminary finding that the illusory motion in depth does not occur even in a black-background stereogram when random-dot patterns do not correspond to each other.

6 General discussion

6.1 *The role of contrast*

The critical role of contrast in the visual-delay illusion, which refers to our anomalous motion illusion (figure 1), was confirmed. That is, the lower the contrast, the longer the latency irrespective of whether the stimulus is dark or light (experiments 1 and 3).

This result, however, disagrees with a preliminary report of the Hess effect given by Wilson and Anstis (1969), who found longer latency for darker stimuli even if the background was of high luminance. Although we regard our illusion as being the same phenomenon as the Hess effect, there remains a possibility that they are different from each other. If so, our anomalous motion illusion is a new phenomenon. To settle this question, it is necessary to examine the Hess effect with our swaying method and compare the result with the present results.

Our finding suggests that the visual-delay illusion should have a stereoscopic effect like the Pulfrich effect (Pulfrich 1922; Rogers and Anstis 1972) if a pattern of low contrast is projected to one eye and the same pattern of high contrast is presented to the other eye, and they are swayed laterally. As a result, illusory motion in depth like the Pulfrich effect was observed when the background was dark, while illusory motion in depth was hardly reported when the background was bright (experiment 4).

This failure might be due to the difficulty of binocular fusion of a white and nearly-white pattern with a black-and-white one (figure 6b).

The effect of contrast was rejected as an explanation of the Pulfrich effect by Dodwell et al (1968) and as that of the Hess effect by Prestrude and Baker (1971). The former suggested the involvement of contrast but did not provide clear evidence. The latter did not obtain positive evidence and the space-average luminance level was thought to account for this effect. Therefore our finding that contrast is significant is quite novel. This discrepancy might be partly due to the difference in stimulus configurations: the previous studies used bars while we adopted random dots.

In addition, there was a tendency that the lower was the contrast the faster was the perceived speed (experiment 2). This result, which is apparently inconsistent with previous reports (Thompson 1982; Stone and Thompson 1992; Blakemore and Snowden 1999; Anstis 2001, 2004), may be due to relatively high speeds that could cause this reversal (Thompson 1982). The effect of speed, however, was not as prominent as that of visual latency and we suggest that the visual-delay illusion chiefly depends on longer visual latency caused by low contrast.

6.2 *The degree of visual delay*

The delay measured in our experiments was up to 30 ms (maximum 44 ms). These values are consistent with those of Prestrude and Baker (1968) (up to 39.4 min), but they are rather shorter than those of Wilson and Anstis (1969) (up to 150 ms) or those of Williams and Lit (1983) (up to 80 ms). Moreover, our values are also shorter than those of the Pulfrich effect (Rogers and Anstis 1972) (up to 100 ms). This discrepancy is too large to be ignored but remains unsolved.

6.3 *A possible mechanism of the visual delay*

Harker (1967) attributed the visual delay of the Pulfrich effect to saccadic suppression. This idea was not supported by Prestrude (1971) and Prestrude and Baker (1968) who studied the Hess effect with a rotating disc instead of a swinging pendulum. We also do not support the saccadic-suppression hypothesis since our anomalous motion illusion can also be observed by rotating figure 1 or by approaching or moving away from it.

The present study showed the critical role of contrast in visual delay. How does low contrast increase visual latency? Our speculation is as follows. When contrast is lower, it takes more time to correctly measure the amount of contrast, because lower contrast means a smaller difference in luminance within the area and noise affects the estimation of contrast to a greater extent. That is, 'contrast detectors' need a constant level of temporal summation of impulses to give their outputs. This speculation can also explain why a dark stimulus produces a longer latency than does a bright stimulus.

6.4 *Can the idea of contrast-dependent visual latency explain other anomalous motion illusions?*

There are at least four types of anomalous motion illusions in which contrast may possibly play a part. One is the fluttering-heart illusion (von Helmholtz 1867/1962; von Kries 1896; von Grünau 1975a, 1975b, 1976; Nguyen-Tri and Faubert 2003) because this illusion is observed at a low-contrast border of two different colours. This feature accords with the finding that low contrast produces a longer latency.

The second one is the swinging-motion illusion (Khang and Essock 2000) because this illusion is observed at the field flanked by low-contrast parts. This observation also agrees with the finding that low contrast produces a longer latency.

The third one is the optimised Fraser – Wilcox illusion (Kitaoka and Ashida 2003) because it was explained in terms of contrast gradient (Backus and Oruç 2005; Conway et al 2005). This explanation also accords with the idea of contrast-dependent visual latency.

The fourth one is the 'central drift' illusion (Kitaoka and Ashida 2004), because this illusion occurs simply along the gradient of contrast. This illusion, however, disagrees with the finding that low contrast gives a longer latency because the direction of illusory motion (from low-contrast to high-contrast) is a reversal of the expected direction.

6.5 *Relationship of our illusion with other anomalous motion illusions*
Our visual-delay illusion is characterised by illusory motion in the same direction as the retinal-image motion. Here we compare our illusion with the other anomalous motion illusions that share this characteristic, which are summarised in table 1 in section 2.2.

First, the visual-delay illusion resembles the fluttering-heart illusion (von Helmholtz 1867/1962; von Kries 1896; von Grünau 1975a, 1975b, 1976; Nguyen-Tri and Faubert 2003). There are, however, three differences between these two illusions. One is that the fluttering-heart illusion depends on a difference in colour, preferring the combination of red and blue, while the visual-delay illusion depends chiefly on a difference in luminance. In this regard, however, Nguyen-Tri and Faubert (2003) recently suggested a possibility that contrast may play a part in the fluttering-heart illusion. The second is that the fluttering-heart illusion is observed more clearly under dark illumination, while the visual-delay illusion is more salient in a bright condition. The third is that the fluttering-heart illusion is observed clearly in peripheral vision, while the visual-delay illusion is fully discernible in the fovea as well. In this regard, the visual-delay illusion appears to be stronger in peripheral vision (see figure 1 in the visual periphery), a feature common to the fluttering-heart illusion. In sum, the fluttering-heart illusion appears to be different from the visual-delay illusion in some aspects, while the two resemble each other in other aspects. The question whether these two illusions are of the same neural origin remains open.

Arnold and Johnston (2003) reported a jittering motion that is seen in the inset of a coherently moving concentric pattern, such as a green dot surrounded by a larger red disc. They suggested that the cause of this effect is the difference in perceived speed, in which the low-contrast border (green versus red) produces a slower perceived speed than the high-contrast one (the other borders). The jittering motion occurs because the visual system occasionally resets the location of the inset when it lags behind too much. Unlike the original fluttering-heart illusion, Arnold and Johnston's observation depends on the difference in luminance contrast as is the case with the visual-delay illusion. However, the difference in perceived speed turned out to have a relatively minor role in our case. The constant delay shown in the visual-delay illusion would not fit their explanation of recalibration. Thus we probably look at different phenomena based upon different mechanisms or at least different aspects of the same mechanism.

The swinging-motion illusion (Khang and Essock 2000) in which an elongated plaid appears to swing horizontally when we shift our gaze horizontally, resembles the visual-delay illusion. Khang and Essock attributed the swinging motion to apparent positional shifts based upon visual latency generated by hysteresis of the gain-setting mechanism to the luminance ramps. Although there is some phenomenological similarity, their explanation cannot be directly applied to the visual-delay illusion because our stimulus does not comprise luminance ramps.

The floating-motion illusion (Pinna and Spillmann 2002), in which a pattern of line drawing appears to move relative to a pattern of painting, resembles the visual-delay illusion. The authors briefly mentioned that this illusion depends on the difference in perceived speed between the area of high spatial frequency and the area of low spatial frequency. If that is true, their floating-motion illusion is quite different from the visual-delay illusion.

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