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REVIEW REPORT

A review of the footsteps illusion

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Abstract

Studies on the footsteps illusion proposed by Anstis (2001) and its variants are reviewed in this article. The footsteps illusion has been explained as a difference in perceived speed depending on edge contrast (Thompson, 1982). In addition to this explanation, it is suggested that the footsteps illusion and its variants can also be attributed to the geometrical illusion presented by Gregory and Heard (1983), to the extinction effect similar to hidden images by Wade (1990), and to subsequent position or motion captures. Related illusions, for example, the kickback illusion (Howe, Thompson, Anstis, Sagreiya, & Livingstone, 2006), the kick-forward illusion, the driving-on-a-bumpy-road illusion, or the footsteps illusion based upon reverse phi motion, are discussed in this article.

Keywords: *footsteps illusion*; *motion perception*; *contrast*; *geometrical illusion*; *extinction effect*; *position capture*; *motion capture*; *reverse phi*

To access the movies for this article, please visit the article landing page or read the html version of the article where all movies are embedded.

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Motion perception is an intriguing subject that has been fascinating vision researchers and artists. It is not simply the perception of a set of different still images that are arranged along a time axis. For example, a motion aftereffect is observed when observers watch a stationary image after seeing a moving object (Anstis, Verstraten, & Mather, 1998). There are several instances of motion illusion in a still image without prior adaptation to motion (Kitaoka, 2014, 2017; Kitaoka & Ashida, 2007; Pinna & Brelstaff, 2001; Spillmann, Saito, & Komatsu, 2016). A change in luminance alone can cause motion perception (Anstis, 1970; Gregory & Heard, 1983; Rogers, Anstis, Ashida, & Kitaoka, 2019).

Although there are a variety of topics in motion perception, the footsteps illusion (Anstis, 2001, 2003, 2004) is particularly intriguing because the object's motion becomes dramatically faster or slower depending on the background. The study of this illusion is expected to help to clarify the mechanism of motion perception. To achieve this goal, we here review the footsteps illusion, its abundant variants, and new related illusions.

The footsteps illusion

The footsteps illusion is a motion illusion in which objects appear to move fast or slow even when they move at a constant speed. For example, when blue or yellow rectangles move horizontally at a constant speed across a stationary grating of vertical black and white stripes, they appear to accelerate or decelerate repeatedly (moving or pausing) like a footstep motion (Movie 1). Each rectangle has the same width as two stripes, so that its leading and trailing edges always lie on the same color (black or white). The rectangles appear to slow down when their moving edges are of lower contrast (blue vs. black; yellow vs. white). Color is not indispensable, and achromatic (dark-gray or light-gray) rectangles instead of the chromatic ones work (Movie 2). The footsteps illusion is also observed when rectangles are black or white and the stripes are dark-gray or light-gray (Movie 3). It is therefore suggested that the essential factor is the luminance contrast of moving edges.

When the rectangles have the same width as three stripes, so that their leading and trailing edges always lie on the different color (black vs. white), the 'inchworm' variant of the

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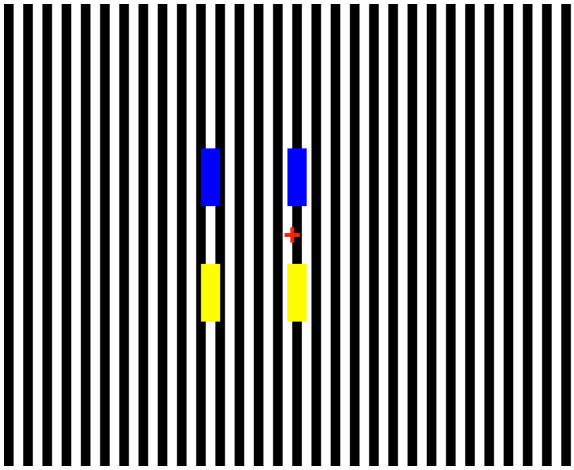
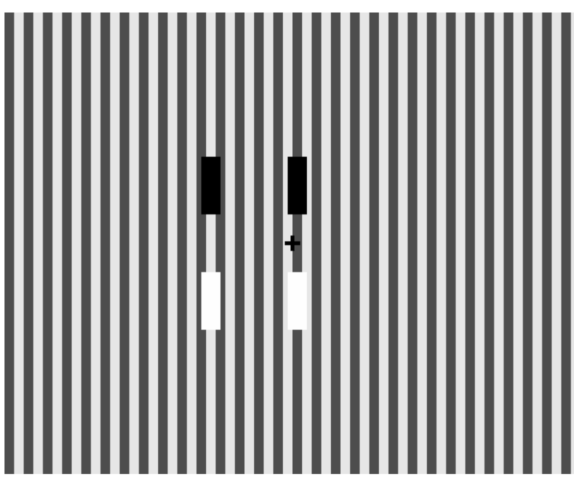
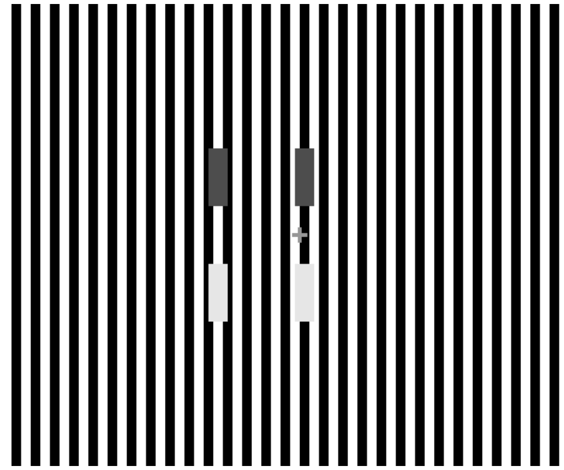


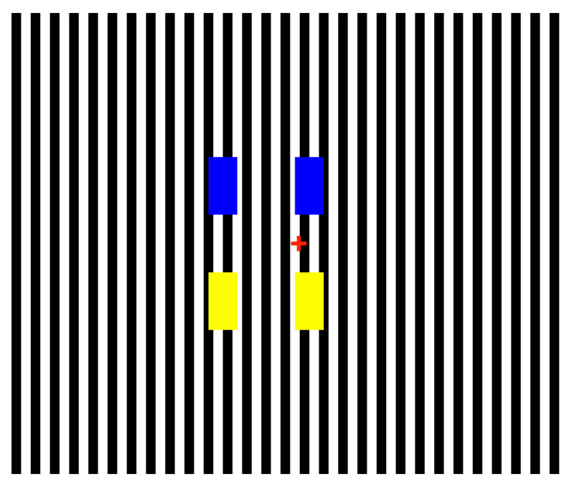
Movie 1. A demonstration of the footsteps illusion. Blue or yellow rectangles (20 pixels wide) move horizontally back and forth at a constant speed (1 pixel per each 30 ms) across a vertical grating made up of black and white stripes (10 pixels wide for each stripe), but they appear to move fast or slow like a footstep motion.



Movie 2. A demonstration of the achromatic version of the footsteps illusion. Dark-gray (R: 77,G: 77, B: 77) or light-gray (R: 230, G: 230, B: 230) rectangles (20 pixels wide) move horizontally back and forth at a constant speed (1 pixel per each 30 ms) across a vertical grating of black and white stripes (10 pixels wide for each stripe), but they appear to move fast or slow like a footstep motion.



Movie 3. A demonstration of the achromatic version of the footsteps illusion. Black and white rectangles (20 pixels wide) move horizontally back and forth at a constant speed (1 pixel per each 30 ms) across a vertical grating of dark-gray (R: 77,G: 77, B: 77) or light-gray (R: 230, G: 230, B: 230) stripes (10 pixels wide for each stripe), but they appear to move fast or slow like a footstep motion.



Movie 4. A demonstration of the inchworm illusion. Blue or yellow rectangles (30 pixels wide) move horizontally back and forth at a constant speed (1 pixel / 30 ms) in front of a vertical grating of black and white stripes (10 pixels wide for each stripe), but they appear to expand and contract as they move.

footsteps illusion is observed (Anstis, 2001) (Movie 4). The rectangles appear to repeatedly expand and contract horizontally. This illusion indicates that the leading and trailing edges independently contribute to the footsteps illusion.

The inverted footsteps illusion

Even when rectangles are stationary and the grating moves, the former appear to move like the footsteps illusion (Movie 5). This illusion was presented by Howe et al. (2006) as their Stimulus 2d demo. Since the rectangles are stationary, this footstep motion is an induced motion. Hereafter, we call this phenomenon as the 'inverted footsteps illusion'.

Anstis (2004) attributed the footsteps illusion to the difference in perceived speed that depends on the difference in luminance contrast. This hypothesis is based upon the observation that gratings of lower contrast appear to move slower than those of higher contrast (Stone & Thompson, 1992; Thompson, 1982).

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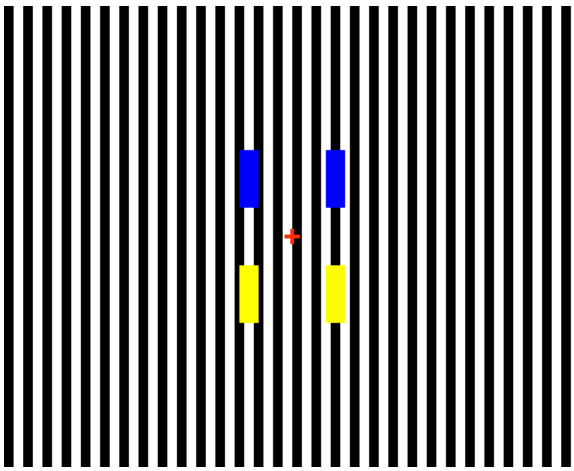
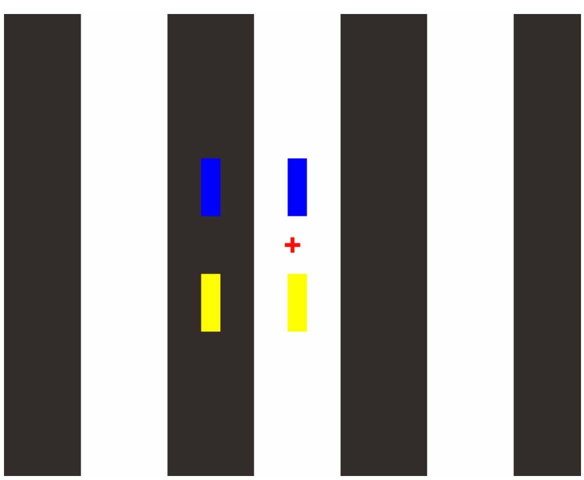
This hypothesis was criticized by Howe et al. (2006), who reported a much weaker footstep appearance when the target moved on a homogeneous background alternating between black and white. This hypothesis cannot be applied to the inverted footsteps illusion, either, because the target is stationary. Yet, it should be stressed that the footsteps illusion based upon the difference in apparent speed depending on edge contrast is observed to some extent (Anstis, 2003) (Movie 6).



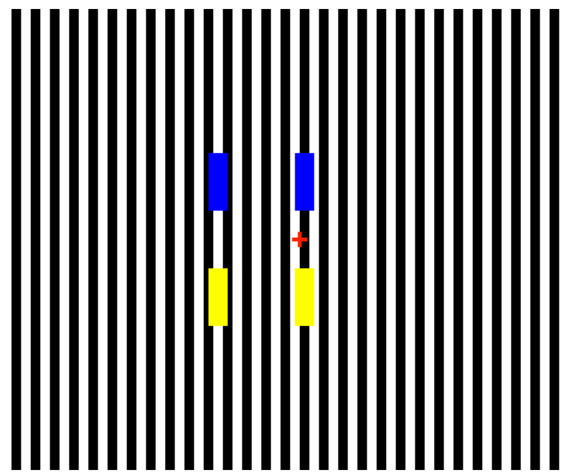
Movie 5. A demonstration of the inverted footsteps illusion proposed by Howe et al. (2006). Blue or yellow rectangles (20 pixels wide) are stationary, and a grating of black and white stripes (10 pixels wide for each stripe) moves rightward at a constant speed (1 pixel / 30 ms) behind the rectangles. Even if observers fixate at the stationary cross, a footstep motion that resembles the footsteps illusion is observed.



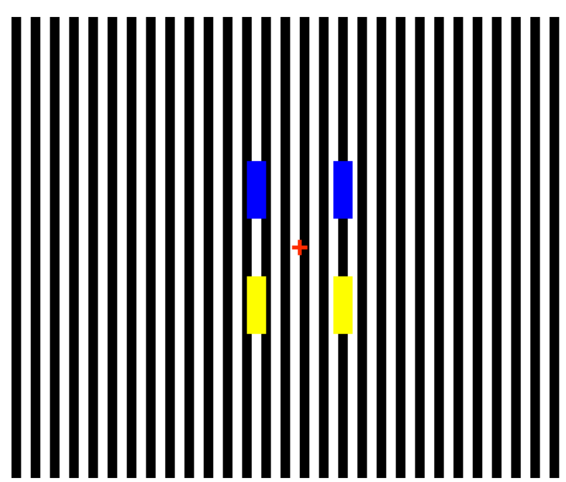
Movie 6. A demonstration of the footsteps illusion based upon the difference in edge contrast. Blue or yellow rectangles (20 pixels wide) move horizontally back and forth at a constant speed (1 pixel / 30 ms) across a grating of black and white stripes (90 pixels wide). Black and white stripes are flipped over Every 300 ms. At that moment, their position moves by 10 pixels so that each rectangle moves in the middle of a stripe and the edges of a rectangle do not touch or step over borders of stripes. A weak footstep motion is observed.

Involvement of position capture and motion capture

Here we demonstrate that the footsteps illusion and the inverted one can be observed well even at a low speed. Movie 7 shows the footsteps illusion at a low speed. When moving edges are of low contrast, the motion appears to slow down or to be captured there. The latter is typically



Movie 7. A demonstration of the footsteps illusion at a low speed. Blue or yellow rectangles move at a constant speed (1 pixel / 300 ms). When moving edges are of low contrast, the motion appears to be slow down or to be captured by the stationary stripes (position capture).



Movie 8. A demonstration of the inverted footsteps illusion at a low speed. The grating moves rightward at a constant speed (1 pixel / 300 ms). When the edges of a rectangle are of low contrast, the rectangle appears to be captured by the moving grating and appears to move with it (motion capture).

referred to as 'position capture' (Murakami & Shimojo, 1993), and the rectangles seem to lie alternately closer together and further apart.

Movie 8 shows the inverted footsteps illusion at a low speed. When the edges of a rectangle are of low contrast, the rectangle appears to be captured by the moving grating and appears to move with it. This phenomenon is typically referred to as 'motion capture', although this term usually indicates the phenomenon that a stationary object contoured by color edges (e.g. red vs. green) of low luminance contrast appears to move, being induced by the surround that moves (Goda & Ejima, 1997; Ramachandran, 1987).

In addition, when the edges of a rectangle are of high contrast in Movie 8, the rectangle seems to undergo induced movement, seeming to move in a direction opposite to the stripe. This may be a partial cause of the inverted footsteps illusion.

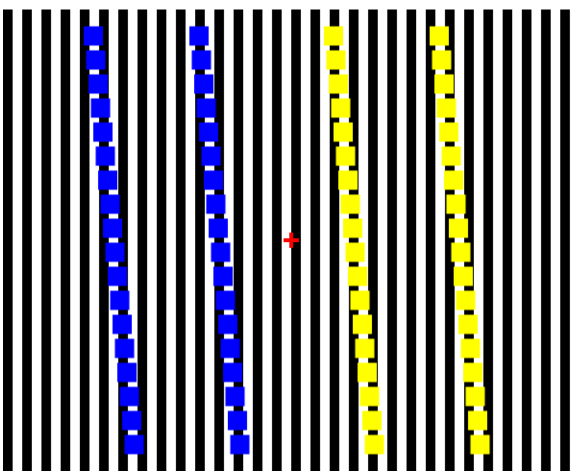
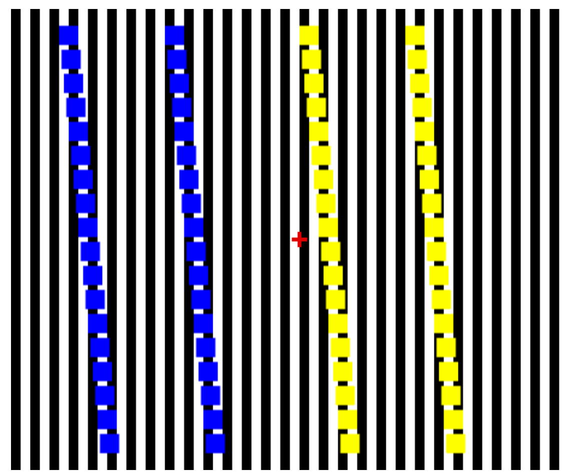


Fig. 1. A demonstration of the Wenceslas illusion. In each color column, blue or yellow squares are aligned in straight lines, but each column appears to undulate as if it were an instance of the Zöllner illusion (Thompson & Anstis, 2005).

Involvement of the geometrical illusion

Thompson and Anstis (2005) suggested a contribution of the geometrical illusion, presenting the Wenceslas illusion. Figure 1 shows an instance, in which multiple squares appear to be placed in an undulating manner although they are aligned in a straight line. This geometrical illusion or position illusion corresponds to the 'belly dancer illusion' that Howe et al. (2006) demonstrated as its moving counterpart (Movie 9).

Subsequently, Sunaga, Sato, Arikado and Jomoto (2008) claimed that the footsteps illusion is an outcome of a geometrical illusion. Figure 2 demonstrates illusory positional shifts of rectangles. In Fig. 2a, the spacing between the upper two blue rectangles appears to be



Movie 9. A demonstration of the belly dancer illusion. Columns of blue or yellow squares (20 pixels wide) that are aligned straightforwardly move horizontally back and forth at a constant speed (1 pixel / 30 ms) across a grating of black and white stripes (10 pixels wide for each stripe). Each column appears to undulate as it traverses the striped background.

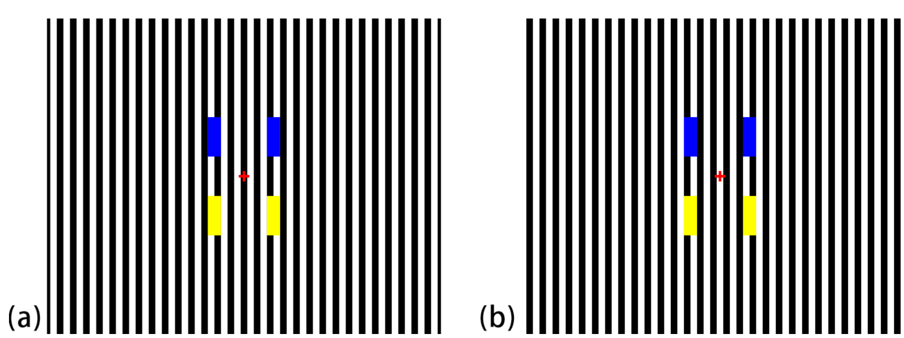


Fig. 2. The geometrical illusion observed in the footsteps illusion. For each image, upper and lower rectangles are aligned vertically. (a) The left edges of the left two rectangles are connected to the right edge of a black stripe, while the right edges of them are connected to the left edge of a white stripe. The opposite is true for the right two rectangles. In this condition, the spacing between the upper two rectangles appears to be larger than the spacing between the lower two. (b) The connections are inverted. The spacing between the upper two rectangles appears to be smaller than the spacing between the lower two.

shorter than the spacing between the lower two yellow rectangles, although they are the same distance apart. On the other hand, in Fig. 2b, the reverse is observed. When a dark object (blue rectangle) is connected to a thin dark object (black stripe), the connected edge appears to shift toward the latter. When a light object (yellow rectangle) is connected to a thin light object (white stripe), the connected edge appears to shift toward the latter. This geometrical-illusion hypothesis can be applied to the inverted footsteps illusion too.

We think that this geometrical illusion should be credited to Gregory and Heard (1983), although Thompson and Anstis (2005) or Sunaga et al. (2008) did not mention it. This issue is described later. For the inchworm illusion (Movie 4), this positional illusion is converted to a size illusion (Fig. 3).

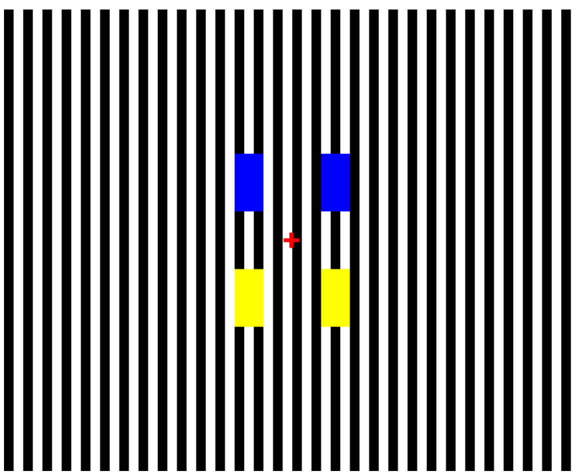


Fig. 3. A size illusion shown in the inchworm illusion. The upper-right blue rectangle and the lower-left yellow one appear to be wider than the upper-left and lower-right ones, although they are of the same size.

Explanations that take into account the capture phenomena and the geometrical illusion

Combining the geometrical illusion (Fig. 2) and the motion phenomena (position capture: Movie 7; motion capture: Movie 8), we explain the footsteps illusion and the inverted one as follows. For the footsteps illusion, let us start with a condition like Fig. 4a in which the edges of the rectangles touch those of the stripes. In this condition, the spacing between the upper two rectangles appears to be smaller than that between the lower two rectangles, although they are the same distance apart. When the rectangles move rightward (Fig. 4b), the upper-left rectangle appears to move slowly or stand still, while the upper-right one appears to move as it does. Thus, the upper spacing appears to increase. On the contrary, the lower-left rectangle appears to move as it does while the lower-right one appears to move slowly or stand still. Thus, the lower spacing appears to decrease. When edges of the rectangles touch those of stripes again (Fig. 4c), the upper spacing appears to be larger than the lower one. Finally, when the rectangles move rightward (Fig. 4d), the upper-left rectangle appears to move as it does while the upper-right one appears to move slowly or stand still. Thus, the upper spacing appears to decrease. On the contrary, the lower-left rectangle appears to move slowly or stand still, while the lower-right one appears to move as it does. Thus, the lower spacing appears to decrease. This repetition makes the rectangles appear to move like a footstep.

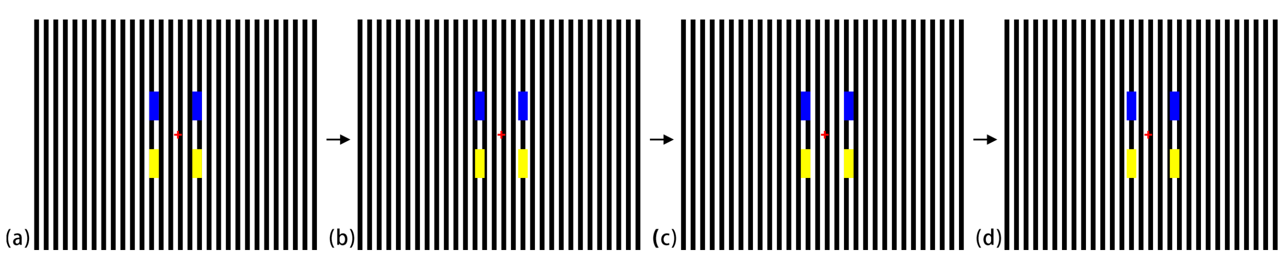


Fig. 4. An explanation of the footsteps illusion with the geometrical illusion and position capture. The stimulus is a periodic change, each cycle consisting of four phases depending on where the edges of rectangles lie. (a) In the condition that the edges of the rectangles touch the edges of stripes like Fig. 2b, the spacing between the upper two rectangles appears to be smaller than the spacing between the lower two rectangles, although they are the same distance apart. (b) When these rectangles move rightward, their edges lie within each stripe. In this phase, the upper-left rectangle appears to move slowly or stand still while the upper-right one appears to move as it does. Thus, the upper spacing appears to increase. On the contrary, the lower-left rectangle appears to move as it does, while the lower-right one appears to move slowly or stand still. Thus, the lower spacing appears to decrease. (c) In the condition that the edges of the rectangles touch the edges of stripes like Fig. 2a, the upper spacing appears to be larger than the lower one. (d) When these rectangles move rightward, their edges lie within each stripe. In this phase, the upper-left rectangle appears to move as it does, while the upper-right one appears to move slowly or stand still. Thus, the upper spacing appears to decrease. On the contrary, the lower-left rectangle appears to move slowly or stand still, while the lower-right one appears to move as it does. Thus, the lower spacing appears to decrease.

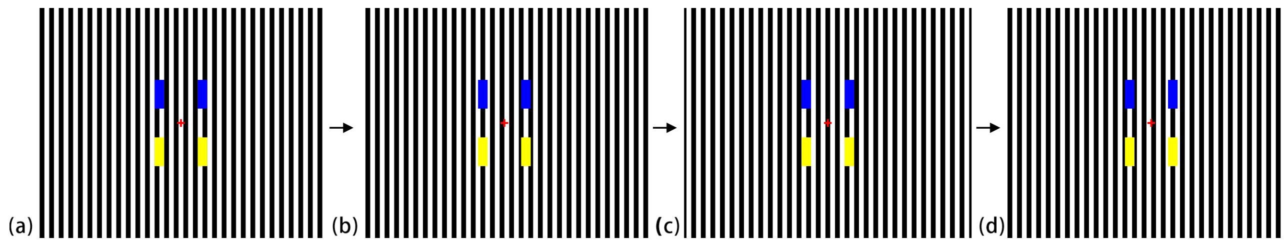


Fig. 5. An explanation of the inverted footsteps illusion with the geometrical illusion and motion capture. The stimulus is a periodic change, each cycle consisting of four phases depending on where the edges of rectangles lie. (a) In the condition that the edges of the rectangles touch the edges of stripes like Fig. 2b, the spacing between the upper two rectangles appears to be smaller than the spacing between the lower two, although they are the same distance apart. (b) When the grating moves rightward, the edges of the rectangles lie within each stripe. In this phase, the upper-left rectangle appears to be stationary as it is while the upper-right one appears to be captured by the moving grating and to move rightward. Thus, the upper spacing appears to increase. On the contrary, the lower-left rectangle appears to be captured by the moving grating and to move rightward, while the lower-right one appears to be stationary as it is. Thus, the lower spacing appears to decrease. (c) In the condition that the edges of the rectangles touch the edges of stripes like Fig. 2a, the upper spacing appears to be larger than the lower one. (d) When the grating further moves rightward, the edges of the rectangles lie within each stripe. In this phase, the upper-left rectangle appears to be captured by the moving grating and to move rightward, while the upper-right one appears to be stationary as it is. Thus, the upper spacing appears to decrease. On the contrary, the lower-left rectangle appears to be stationary as it is, while the lower-right one appears to be captured by the moving grating and to move rightward. Thus, the lower spacing appears to decrease.

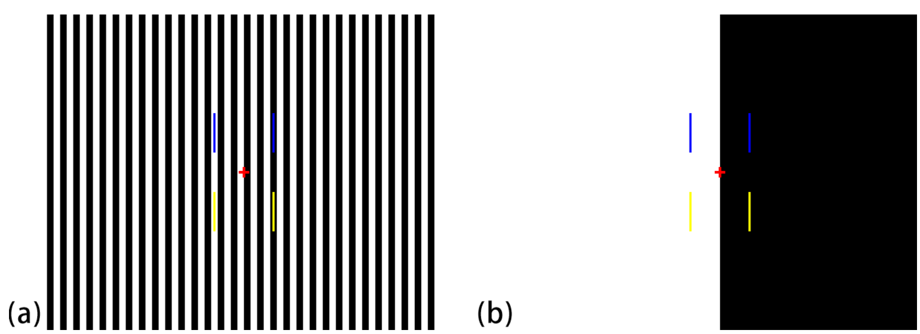


Fig. 6. An extinction effect of edges of low contrast. (a) A grating condition. The upper-right blue thin line segment embedded in a black stripe and the lower-left yellow line segment embedded in a white stripe, that is, edges of low contrast, appear to extinguish rapidly when observers fixate at the cross. The other two line segments of high contrast hardly appear to extinguish. (b) A homogeneous-background condition. Although the upper-right and lower-left ones are of low contrast, they do not appear to extinguish rapidly.

For the inverted footsteps illusion, let us start with a condition like Fig. 5a in which the edges of rectangles touch those of the stripes. In this condition, the spacing between the upper two rectangles appears to be smaller than that between the lower two rectangles, although they are the same distance apart. When the grating moves rightward behind the rectangles (Fig. 5b), the upper-left rectangle appears to be stationary as it is while the upper-right one appears to be captured by the moving grating and to move rightward. Thus, the upper spacing appears to increase. On the contrary, the lower-left rectangle appears to be captured by the moving grating and to move rightward, while the lower-right one appears to be stationary as it is. Thus, the lower spacing appears to decrease. When edges of the rectangles touch those of stripes again (Fig. 5c), the upper spacing appears to be larger than the lower one. Finally, when the grating moves rightward (Fig. 5d), the upper-left rectangle appears to be captured by the moving grating and to move rightward while the upper-right one appears to be stationary as it is. Thus, the upper spacing appears to decrease. On the contrary, the lower-left rectangle appears to be stationary as it is while the lower-right one appears to be captured by the moving grating and to move rightward. Thus, the upper spacing appears to increase. This repetition makes the rectangles appear to move like a footstep.

Involvement of the extinction effect

There is a possibility that the position capture phenomenon observed in the footsteps illusion (Movie 7) and the motion capture phenomenon found in the inverted footsteps illusion (Movie 8) could be attributed to an extinction effect of edges of low contrast in a special condition.

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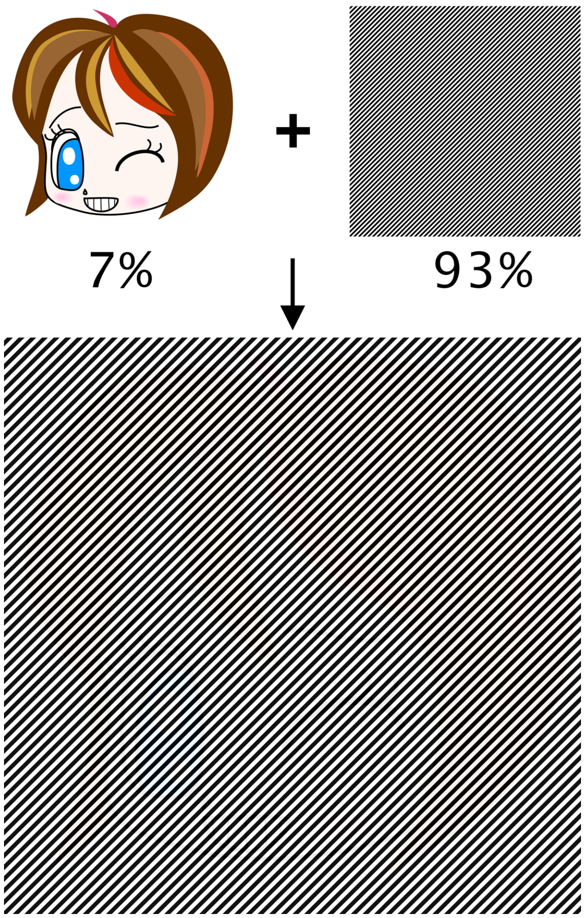
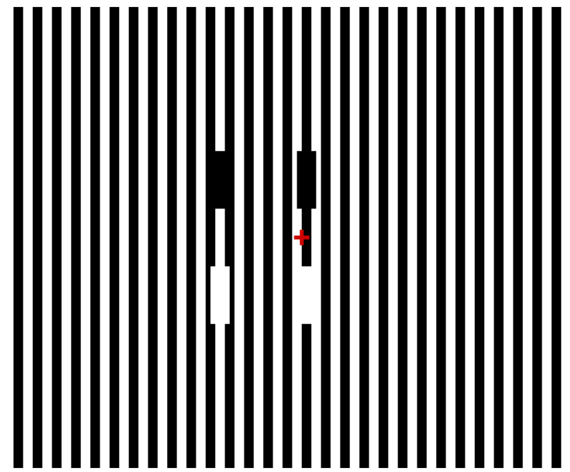


Fig. 7. A demonstration of the extinction effect on edges of low contrast due to nearby edges of high contrast or components of high spatial frequency. An illustrated girl's face of low contrast is embedded in a fine grating of high contrast, the face is hard to see when the high-contrast edges are clearly seen. When the image is blurred or is seen from a distance, or if the page is rapidly jiggled, the face is more discernible. This extinction effect is closely related to 'hidden images' (Wade, 1990). Both share the effect that 'high-contrast, high spatial frequency contours can suppress the visibility of low-contrast, low spatial frequency components within them' (Wade, 2017).

Figure 6a demonstrates that thin line segments of low contrast appear to extinguish rapidly when observers fixate at the cross. When objects are placed on a homogeneous background, they do not appear to extinguish soon (Fig. 6b). It is suggested that the essential factor be a combination between edges of low contrast and edges of high contrast close to the former (Fig. 7). In the chapter entitled 'Hidden images', Wade (2017) mentioned that high-contrast, high spatial frequency contours can suppress the visibility of low-contrast, low spatial frequency components within them. This suggestion is consistent with Zenger-Landolt and Koch (2001) who reported that the apparent contrast of an edge is reduced by surrounding edges of high contrast. It is plausible that this



Movie 10. A demonstration of the special case of the footsteps illusion. Black or white rectangles (20 pixels wide) move horizontally back and forth at a constant speed (1 pixel / 30 ms) in front of a grating of black and white stripes (10 pixels wide for each stripe). They appear to move fast or slow like a footstep motion. Besides the involvement of the geometrical illusion, this perception is explained with position capture due to the lack of motion signals where 'moving' edges do not exist physically.

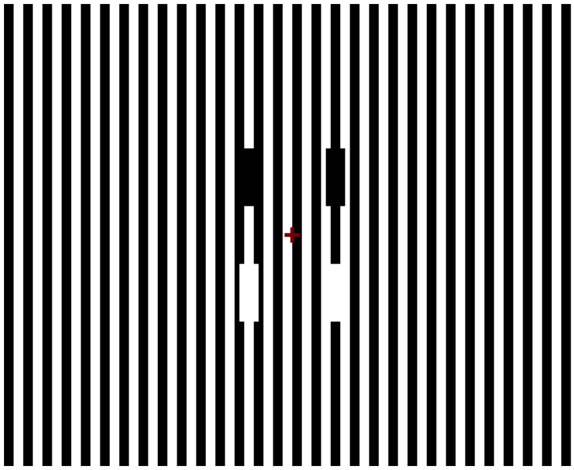
extinction effect causes the position capture and motion capture of edges of low contrast in the footsteps illusion and the inverted footsteps illusion, respectively.

Moreover, the footsteps illusion and the inverted one are observed even when blue and yellow rectangles are replaced with black and white ones, respectively (Movies 10 and 11). In this footsteps illusion, position capture occurs when there are no physical motion signals, that is, when the edges of a black rectangle lie inside a black stripe or those of a white rectangle stay inside a white stripe. This variant was presented in Howe et al. (2006), who reported a strong illusion. In the inverted footsteps illusion, motion capture occurs when there are no physical motion signals, which would induce imaginary rectangles to move. It is suggested that the original footsteps illusion (Movie 1) and its inverted one (Movie 5) be attributed to or be equivalent to these variants through the process of the extinction effect.

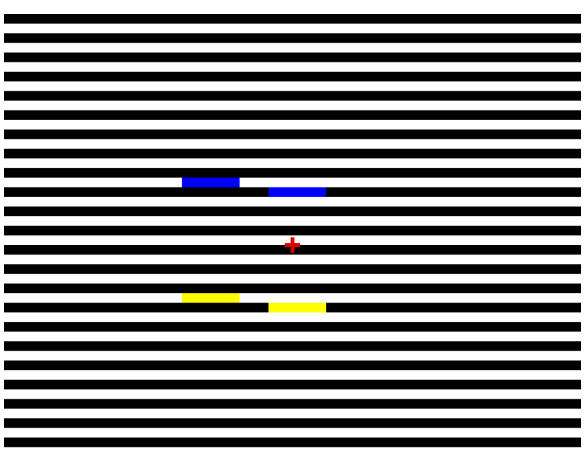
Other variants of the footsteps illusion

The horizontally elongated variant

The extinction-effect hypothesis may help to explain another footstep phenomenon presented by Howe et al. (2006, their Stimulus 2e demo) (Movie 12). In their stimulus, both rectangles and stripes are elongated horizontally, and the height of each rectangle is the same as that of each stripe. The upper and lower sides of a rectangle touch the lower edge of the upper stripe and the upper edge of the lower stripe, respectively. When one horizontally moves



Movie 11. A demonstration of the inverted variant of the special case of the footsteps illusion. Black or white rectangles are stationary, and the grating moves rightward at a constant speed (1 pixel / 30 ms) behind the rectangles. Even if observers fixate on the stationary cross, a footstep motion is observed. Besides the involvement of the geometrical illusion, this perception is explained with motion capture due to the lack of motion signals where 'stationary' edges of rectangles do not exist physically.



Movie 12. A demonstration of another footsteps illusion presented by Howe et al. (2006). Blue or yellow rectangles (10 pixels height and 30 pixels wide) move horizontally back and forth at a constant speed (1 pixel / 30 ms) on black or white stripes. These stripes alternate over every 300 ms. The rectangles appear to move fast or slow like a footstep motion synchronously with the alternation of stripes.

a blue rectangle that is placed on a black stripe and is sandwiched by the upper and lower white stripes (e.g. the upper-right rectangle of Fig. 8: #1), the blue rectangle appears to move behind a yellow rectangle that is placed in the same condition (e.g., the lower-right rectangle of Fig. 8: #2). When one horizontally moves a yellow

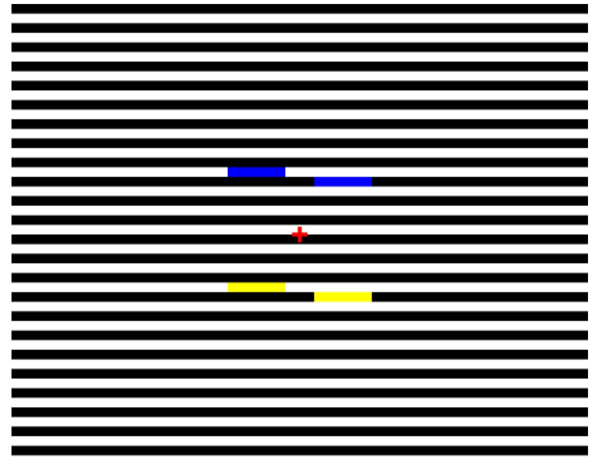


Fig. 8. One of the frames of Movie 12. The upper-right blue and the lower-left yellow rectangles appear to be indistinct or sometimes appear to extinguish, while the other two are perceived clearly.

rectangle that is placed on a white stripe and is flanked by the upper and lower black stripes (e.g., the lower-left rectangle of Fig. 8: #3), the yellow rectangle appears to move behind a blue rectangle that is placed in the same condition (e.g., the upper-left rectangle of Fig. 8: #4). The extinction effect is observed for the rectangles #1 or #3, which appear to be indistinct or sometimes disappear.

This horizontally elongated variant (Movie 12) is not so strong as the original (Movie 1), as pointed out by Howe et al. (2006) who suggested the involvement of an additional mechanism. This suggestion is discounted as follows. One plausible reason is that this variant is not accompanied by the geometrical illusion. Another one is that there is no clue to position capture, although the rectangles #1 and #3 show the extinction effect. It is therefore suggested that the weak footsteps illusion observed in this variant be equivalent to the footsteps illusion based solely upon the difference in apparent speed depending on edge contrast (Anstis, 2003) (Movie 6). Moreover, movies in which the stripes repetitively reverse their polarity over time (such as Movie 12) give rather weak effects, which are generally masked by a strong apparent motion in which the blue and yellow bars appear to jump back and forth.

The enhanced version of the horizontally elongated variant

Movie 13 shows a new version of the horizontally elongated variant, which presents a much stronger footstep motion comparable to the original footsteps illusion (Movie 1). Blocks of horizontally elongated rectangles move horizontally across a stationary checkerboard pattern instead of the alternating stripes (Fig. 9). Moving edges of low contrast (blue vs. black or yellow vs. white) appear to move slower than those of high contrast or to pause there (position capture).

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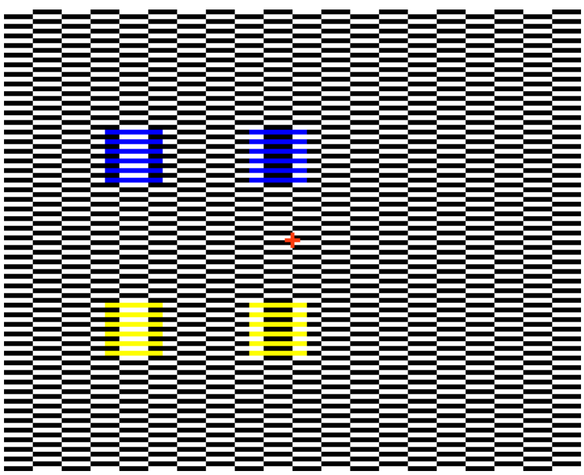
Movie 14 shows its inverted one, in which rectangles are stationary and the checkerboard pattern moves. Stationary lateral edges of low contrast appear to be captured by the moving checkerboard pattern and to move with it (motion capture), while those of high contrast appear to be stationary as they are.

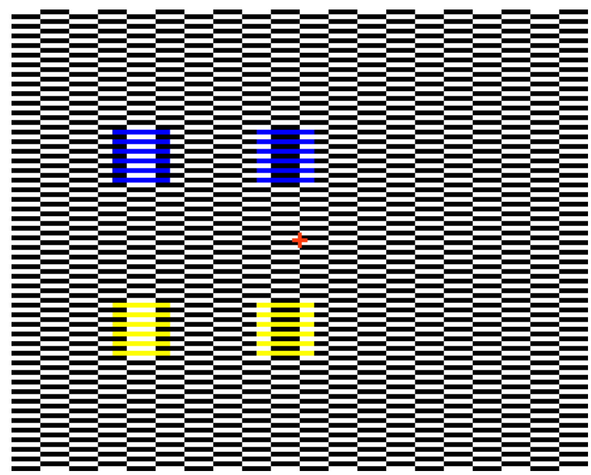
This footsteps illusion or the inverted one is observed even if rectangles or the checkerboard move slowly (Movies 15 and 16). Moreover, the geometrical illusion does not seem to be involved in these variants (Fig. 9). These observations suggest that these horizontally elongated variants chiefly depend on the extinction effect and subsequent capture phenomena in addition to the difference in apparent speed depending on edge contrast.

The railroad-track variant

In the railroad-track variant of the footsteps illusion (Anstis, 2004), rectangles move across a grating of the same height (Movie 17). Although this variant is as strong as the original one, Howe et al. (2006) regarded it as a problem that the illusion is somewhat reduced in comparison to the standard one. We suggest that the reduction, if any, depends on a weaker extinction effect because there is a relatively small amount of edges of high contrast.



Movie 13. A demonstration of the enhanced version of the horizontally elongated variant. Blocks of blue or yellow rectangles (5 pixels height and 60 pixels wide for each rectangle) move horizontally back and forth at a constant speed (3 pixels / 30 ms) across a checkerboard pattern or along rows of black or white rectangles (5 pixels height and 30 pixels wide for each rectangle). When moving edges are of low contrast (blue vs. black or yellow vs. white), they appear to move behind those of high contrast or to be captured there (position capture).



Movie 14. A demonstration of the inverted variant of the enhanced version of the horizontally elongated footsteps illusion. Blocks of blue or yellow rectangles (5 pixels height and 60 pixels wide for each rectangle) are stationary and the checkerboard pattern of black or white rectangles (5 pixels height and 30 pixels wide for each rectangle) move rightward at a constant speed (3 pixels / 30 ms). When the lateral edges of rectangles are of low contrast (blue vs. black or yellow vs. white), they appear to move slowly or to be captured by the moving checkerboard and move with it (motion capture).

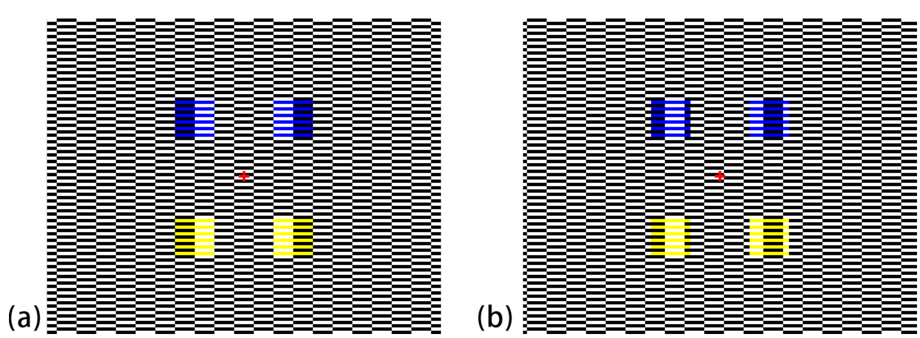
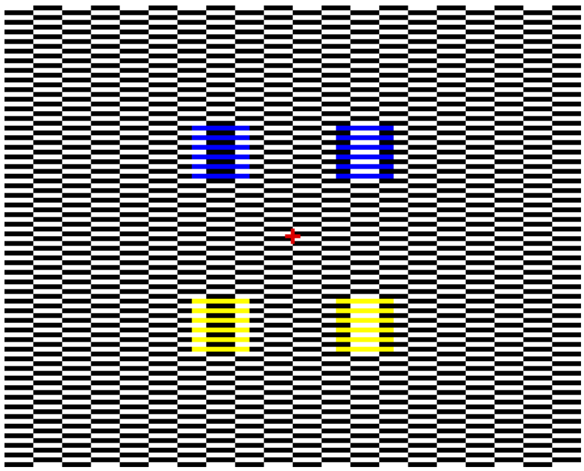
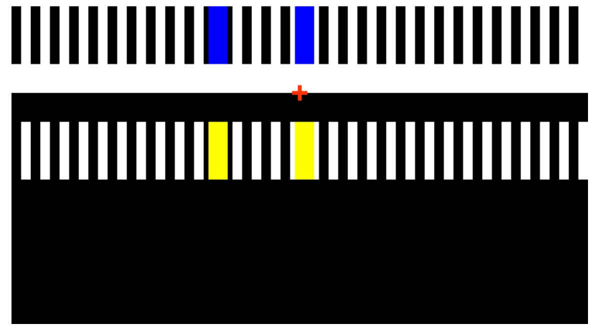


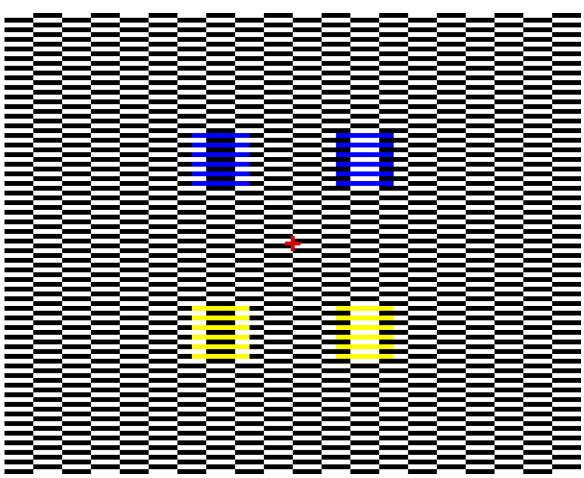
Fig. 9. Frames of the enhanced version of the horizontally elongated variant. There is little or no positional illusion in the enhanced version of the horizontally elongated variant. Panel (a) shows the condition where the lateral edges of blue or yellow rectangles are aligned with vertical, phase-flipping borders of the checkerboard pattern. Panel (b) shows the other condition.



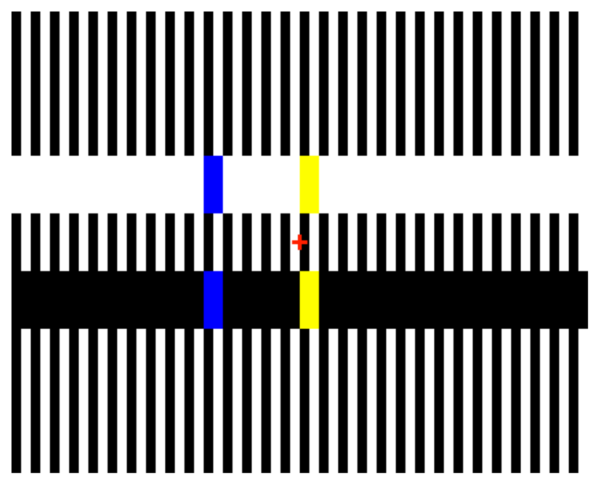
Movie 15. A demonstration of the enhanced version of the horizontally elongated variant at a low speed (3 pixels / 300 ms). Position capture is observed.



Movie 17. A demonstration of the rail-track variant of the footsteps illusion. Each of the blue or yellow rectangles (60 pixels high × 20 pixels wide) moves horizontally back and forth at a constant speed (1 pixel / 30 ms) across a grating of black and white rectangles (60 pixels high × 10 pixels wide for each rectangle). The top and bottom of the moving rectangles are aligned with those of the grating. A strong footstep motion comparable to the original footsteps illusion is observed.



Movie 16. A demonstration of the inverted variant of the enhanced version of the horizontally elongated footsteps illusion at a low speed (3 pixels / 300 ms). Motion capture is observed.

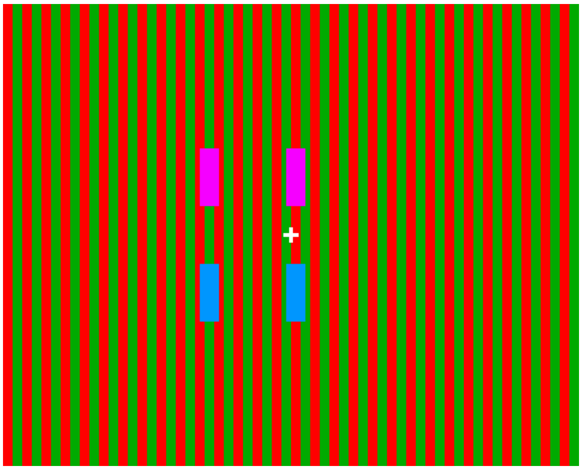


Movie 18. A demonstration of the clearing-in-a-forest variant. Each of the blue or yellow rectangles (60 pixels high × 20 pixels wide) moves horizontally back and forth at a constant speed (1 pixel / 30 ms) across a white or black gap between gratings of black and white rectangles (60 pixels high × 10 pixels wide for each rectangle).

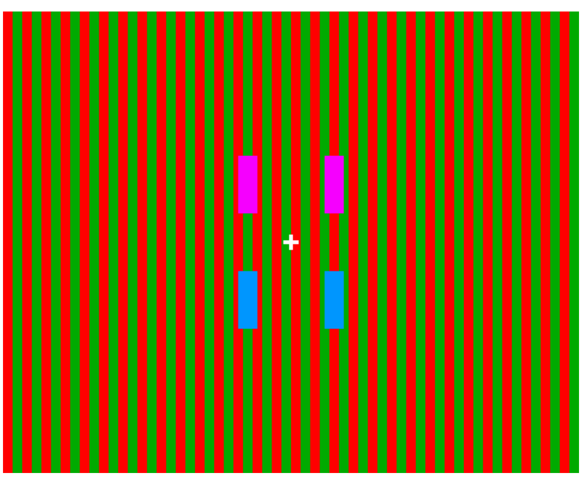
Movie 18 shows the clearing-in-a-forest variant (Anstis, 2004), in which little or no footsteps illusion is observed. This observation indicates that the lateral sides of the moving blocks do not contribute significantly to the footsteps illusion.

The color-based variant

Variants of the 'second-order' footsteps illusion (Kitaoka & Anstis, 2015) can be explained in the same way. For example, Movie 19 demonstrates the color-based footsteps illusion, in which magenta or cyan rectangles appear to show a footstep motion across a grating of red and green stripes, although this footsteps illusion is rather weak for some observers. Edges of low color contrast (combination of similar colors: magenta vs. red, or cyan vs. green) appear to move slower than edges of high color contrast (combination of nearly opponent colors: magenta vs. green; cyan vs. red) or appear to move slowly or to be captured there (position capture). Movie 20 demonstrates the inverted version, which also shows a footstep appearance. Moreover, the geometrical illusion is observed (Fig. 10), which is also thought to contribute to the color-based footsteps illusion and the inverted one. Although the four colors are selected so as to have similar luminances, it



Movie 19. A demonstration of the color-based footsteps illusion. Magenta (R: 245, G: 0, B: 255) or cyan (R: 0, G: 150, B: 255) rectangles (20 pixels wide) move horizontally back and forth at a constant speed (1 pixel / 30 ms) across a grating made up of red (R: 255, G: 0, B: 0) and green (R: 0, G: 170, B: 0) stripes (10 pixels wide for each). The rectangles appear to move fast or slow like a footstep motion.



Movie 20. A demonstration of the inverted variant of the color-based footsteps illusion. Magenta or cyan rectangles are stationary and a grating of red and green stripes moves rightward at a constant speed (1 pixel / 30 ms) behind the rectangles. Even if observers fixate on the stationary cross, a footstep-like appearance is observed.

should be noted that there remains a possible involvement of luminance in this variant.

The contrast-modulated variant

Movie 21 shows a footsteps illusion defined by the difference in luminance contrast (Kitaoka & Anstis, 2015). When moving edges of a square have a small difference in contrast, it appears to slow down, as compared to those that have a large difference in contrast. It is suggested that edges with a small difference in contrast might be hard to be detected in visual processing and appear to slow down or to be captured there.

Movie 22 shows its inverted condition, which, however, does not show a footstep motion or display a weak one at best. This finding is unique as compared with the other inverted variants demonstrated so far. It is conjectured because stationary random-dot patterns anchor the squares there. In contrast, the moving squares in the contrast-modulated footsteps illusion (Movie 21) are perceived as transparent layers and are not anchored by random dots.

Moreover, the geometrical illusion is observed (Fig. 11). It is suggested that it also contributes to the contrast-modulated footsteps illusion and the inverted one.

The offset-defined variant

Movie 23 shows a footsteps illusion defined by the difference in offset of abutting gratings (Kitaoka & Anstis, 2015). Blocks contoured by abutting gratings with a small offset appear to move slower than those with a large offset. It is suggested that subjective contours with a small offset might be hard to be detected in visual processing and appear to slow down or to be captured there. Movie 24 shows its inverted variant, which shows a footstep motion. Moreover, the geometrical illusion is observed (Fig. 12) and is thought to contribute to the offset-based footsteps illusion and the inverted one.

The kickback illusion and the kick-forward illusion

Howe et al. (2006) proposed a new motion illusion called the ‘kickback illusion’. Movie 25 shows an instance in which blue rectangles move across a grating made up of white pinstripes on a black background, while yellow rectangles move across a grating of black pinstripes on a white background. The spacing of two adjacent pinstripes is the same as the width of each rectangle. When the edges of a rectangle pass over pinstripes, the rectangle appear to wiggle or jump backward. To be more specific, this effect occurs both when the leading edge covers a pinstripe and when the trailing edge uncovers a pinstripe (Movie 26). Howe et al. (2006) reported that most subjects reported the backward speed to be considerably greater than the forward speed.

Although the kickback illusion is observed even if rectangles move slowly (Movie 27), the geometrical illusion does not seem to be involved in this effect (Fig. 13). Moreover, the extinction effect might take part when the edges move between pinstripes and slow down the rectangles, but it cannot explain the backward motion of the kickback illusion.

Howe et al. (2006) stated that one would expect the footsteps illusion and the kickback illusion to be

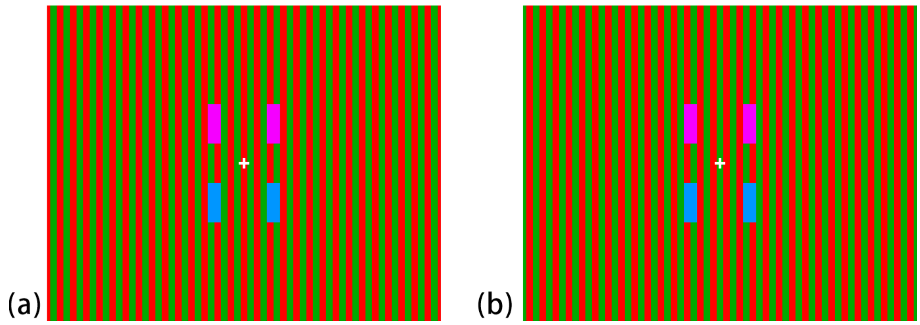
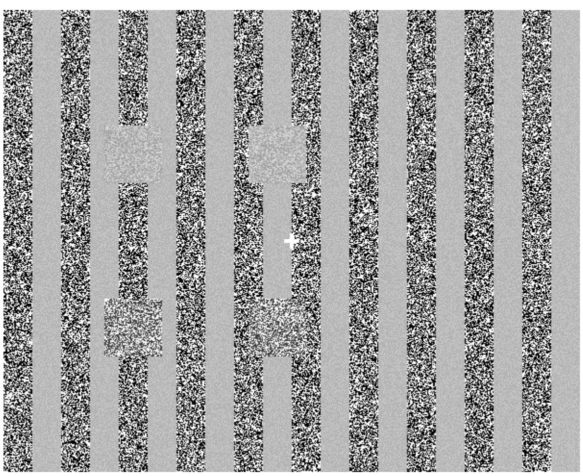
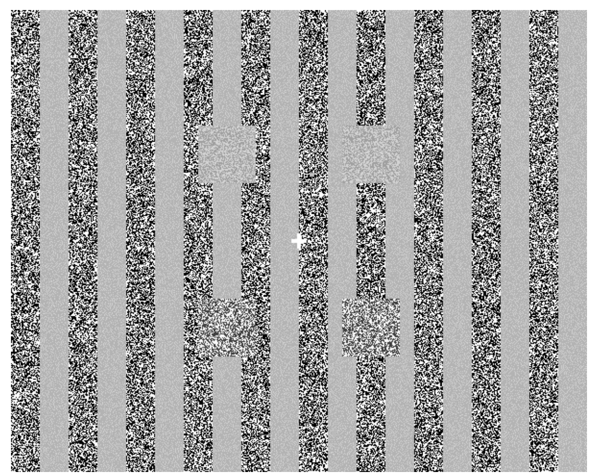


Fig. 10. A footstep-like positional illusion observed in the color-based footsteps illusion. For each image, upper and lower rectangles are aligned vertically. (a) The left edges of the upper-left magenta rectangle and the lower-left cyan one are connected to the right edge of a red stripe, and the right edges of them are connected to the left edge of a green stripe. The opposite is true for the right two rectangles. The spacing between the upper two rectangles appears to be larger than that between the lower two. (b) The connections are inverted. The spacing between the upper two rectangles appears to be shorter than that between the lower two.



Movie 21. A demonstration of the contrast-modulated footsteps illusion. The pattern of random dots (1 × 1 pixel for each dot) is stationary all over the period, while luminance contrast is modulated. The background grating consists of high-contrast and low-contrast stripes (30 pixels wide for each stripe). Moving objects are high-contrast or low-contrast squares (60 × 60 pixels). The contrast of the high-contrast stripes (0 vs. 255 in a 256-level grayscale) is higher than that of the high-contrast squares (63 vs. 249), whereas the contrast of the low-contrast stripes (179 vs. 196) is lower than that of the low-contrast squares (160 vs. 211). Squares move horizontally back and forth at a constant speed (3 pixel / 60 ms) across the stripes. Squares appear to move fast or slow like a footstep motion. Note that the difference in contrast between the high-contrast stripes and the high-contrast squares is so small that some displays cannot properly demonstrate this illusion because of clipping.



Movie 22. A demonstration of the inverted variant of the contrast-modulated footsteps illusion. The contrast-defined squares and the pattern of random dots are stationary and the contrast-defined stripes move rightward at a constant speed (3 pixel / 60 ms) behind the squares. Squares do not appear to show a footstep motion or appear to display a weak one at best.

mediated by the same mechanisms because of their geometric similarity, but that it is probably not the case. They presented two pieces of evidence. One is that the kickback illusion disappears when yellow objects move across white pinstripes on a black background. The other is that the ‘kick-forward’ effect (Movie 28) is observed instead of the kickback one when white objects move across black stripes on a yellow background. The kick-forward illusion also occurs both when the leading edge covers a pinstripe and when the trailing edge uncovers a pinstripe. They suggested that the ‘kick’ part of the kickback illusion is an example of the reverse phi (reversed phi) phenomenon (Anstis, 1970; Anstis & Rogers, 1975, 1986; Rogers et al., 2019).

Movie 28 shows an instance of the kick-forward illusion, in which moving rectangles appear to be accelerated when their edges pass over pinstripes. This illusion gives a strong impression of the footstep motion. The kick-forward effect is observed even if rectangles move slowly

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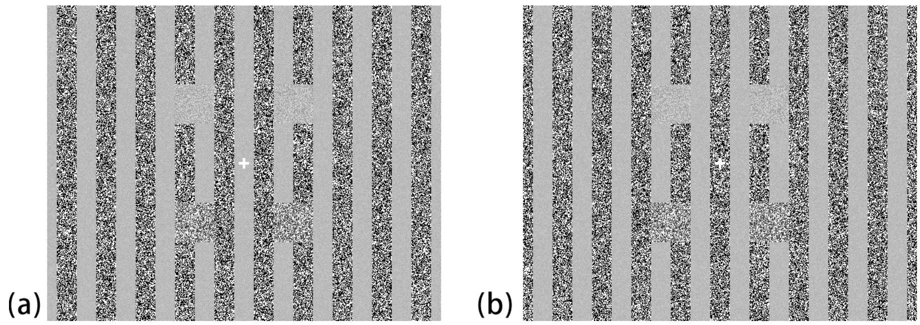
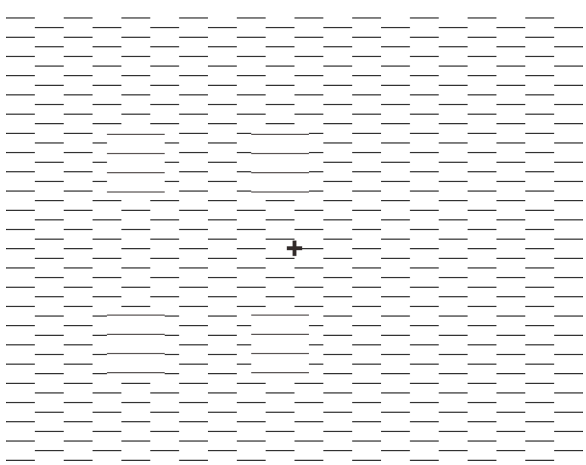
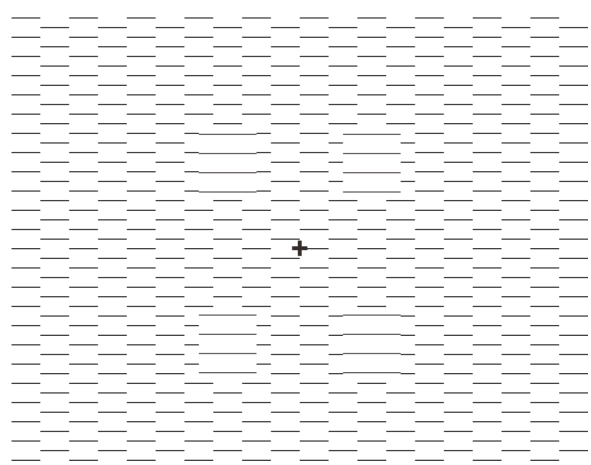


Fig. 11. The geometrical illusions observed in the contrast-modulated footsteps illusion. (a) The spacing of the upper two squares appears to be larger than that of the lower two, though they are aligned vertically. (b) The lower spacing appears to be larger than the upper one. For some observers, the geometrical illusions may be hard to see because the lower squares are hard to see.



Movie 23. A demonstration of the offset-based footsteps illusion. Rectangular blocks made up of four thin line segments (1 pixel high × 60 pixels wide for each line segment; 20 pixels apart) move horizontally back and forth at a constant speed (3 pixels / 60 ms) in front of abutting gratings (30 pixels wide). The lateral edges of the blocks are subjective contours with a large offset or a small one. The blocks appear to move fast or slow like a footstep motion.



Movie 24. A demonstration of the inverted variant of the offset-based footsteps illusion. Blocks are stationary and abutting gratings move rightward at a constant speed (3 pixels / 60 ms) behind the blocks. Even if observers fixate at the stationary cross, a footstep-like appearance is observed.

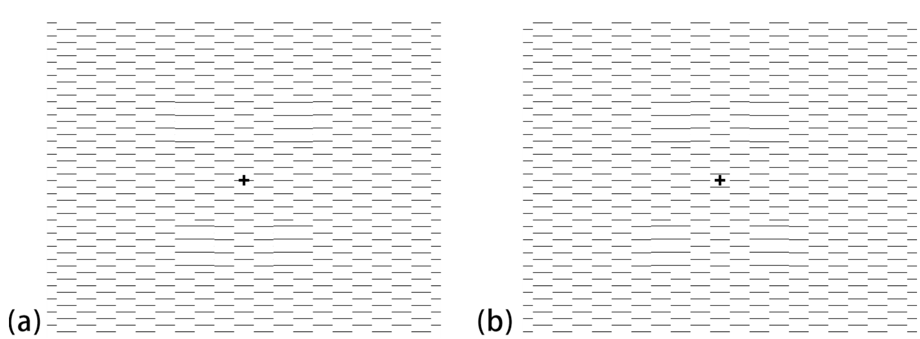
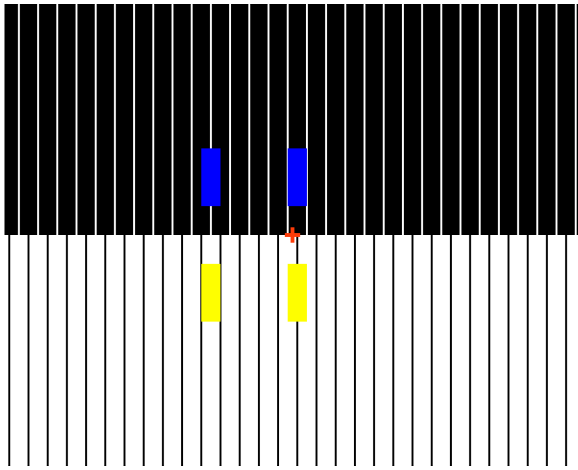
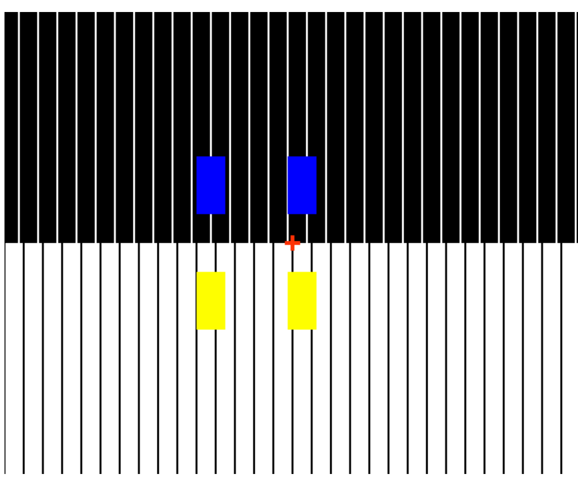


Fig. 12. The geometrical illusions observed in the offset-based footsteps illusion. (a) The spacing of the upper two blocks appears to be larger than that of the lower two, although they are aligned vertically. (b) The lower spacing appears to be larger than the upper one.

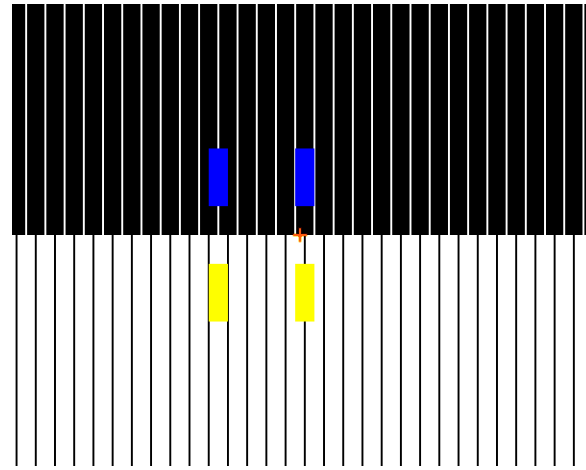


Movie 25. A demonstration of the kickback illusion. Blue or yellow rectangles (20 pixels wide) move horizontally back and forth at a constant speed (1 pixel / 30 ms) in front of a grating made up of white or black pinstripes (2 pixels wide for each pinstripe; inter-pinstripe spacing: 20 pixels) on black or white backgrounds, respectively. Rectangles appear to jump backward when their edges pass over pinstripes.



Movie 26. A demonstration of the kickback illusion to show that this illusion independently occurs at both the leading and trailing edges. Blue or yellow rectangles (30 pixels wide) move horizontally back and forth at a constant speed (1 pixel / 100 ms) in front of a grating made up of white or black pinstripes (2 pixels wide for each pinstripe; inter-pinstripe spacing: 20 pixels) on black or white backgrounds, respectively. The leading/trailing edge of a rectangle appears to jump backward when it covers/uncovers a pinstripe.

(Movie 29) and the geometrical illusion does not seem to be involved in this effect. These observations suggest that the strong impression of the footstep motion be rendered by the alternation between the deceleration caused by the extinction effect when edges move between pinstripes and



Movie 27. A demonstration of the kickback illusion at a low speed. Blue or yellow rectangles move horizontally at a constant speed (1 pixel / 100 ms) in front of a grating of pinstripes. Rectangles appear to jump backward when their edges pass over pinstripes.

the acceleration caused by the kick-forward effect when edges pass over pinstripes.

Movies 30 and 31 show the inverted versions of the kickback and kick-forward illusions, respectively. In these cases, illusory motion can be explained in the same manner as those of the kickback or kick-forward illusions.

As Howe et al. (2006) suggested, the 'kick' part of the kickback illusion or the kick-forward one cannot be explained in the same manner as the footsteps illusion. Their inverted variants cannot be explained so, either. Although Howe et al. attributed the effect to the reverse phi phenomenon (Anstis, 1970; Anstis & Rogers, 1975, 1986) and we basically agree with them, we here specify the illusion that yields the 'kick' part.

Movie 32 shows an instance, in which disks appear to expand or contract when circumference contours appear or disappear. Specifically, a blue disk in the upper-left square appears to expand when its white contour appears, while it appears to contract when the contour disappears. The expansion or contraction is illusory because the blue disk does not change in size. Inversely, a black disk in the upper-right square appears to contract when its white contour appears, while it appears to expand when the contour disappears, although the black disk does not change in size. In the same manner, a yellow disk in the lower-left square appears to expand when its black contour appears, while it appears to contract when the contour disappears. Inversely, a white disk in the lower-right square appears to contract when its black contour appears, while it appears to expand when the contour disappears. This luminance-change-dependent motion illusion was proposed as one of the basic effects

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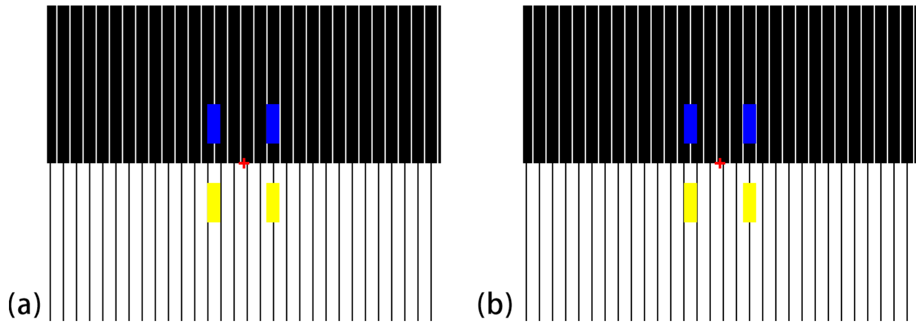
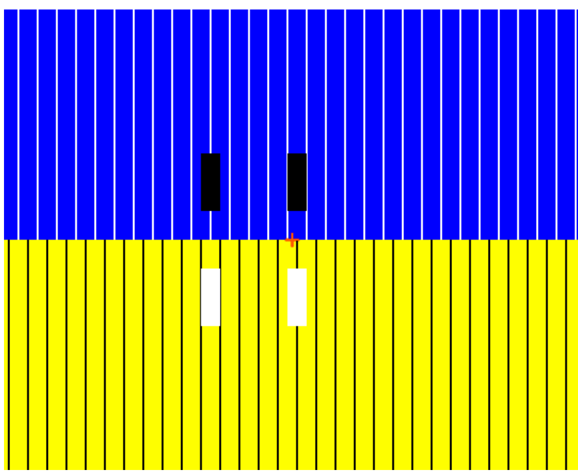
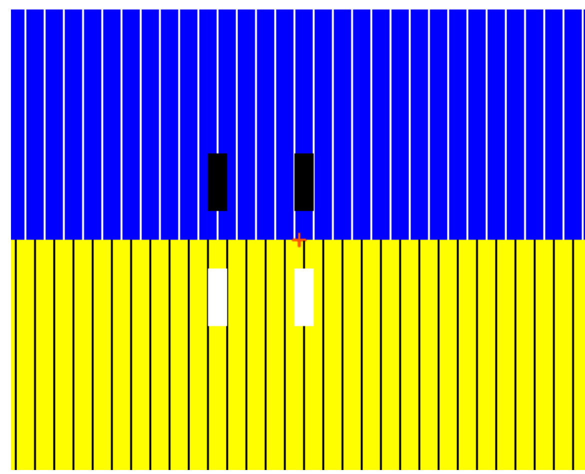


Fig. 13. There is little or no footstep-like positional illusion in the kickback illusion. Panel (a) shows the condition that the right edge of the upper-right blue rectangle and the right edge of the lower-left yellow rectangle touch white and black stripes, respectively. Panel (b) shows the condition that both edges of the upper-right blue rectangle and both edges of the lower-left yellow rectangle touch white and black stripes, respectively.



Movie 28. A demonstration of the kick-forward illusion. Black or white rectangles (20 pixels wide) move horizontally back and forth at a constant speed (1 pixel / 30 ms) in front of a grating made up of white or black pinstripes (2 pixels wide for each pinstripe; inter-pinstripe spacing: 20 pixels) on blue or yellow backgrounds, respectively. The rectangles appear to speed up when their edges pass over pinstripes.



Movie 29. A demonstration of the kick-forward illusion at a low speed. Blue or yellow rectangles move horizontally at a constant speed (1 pixel / 100 ms) in front of a grating of pinstripes. The rectangles appear to speed up when their edges pass over pinstripes.

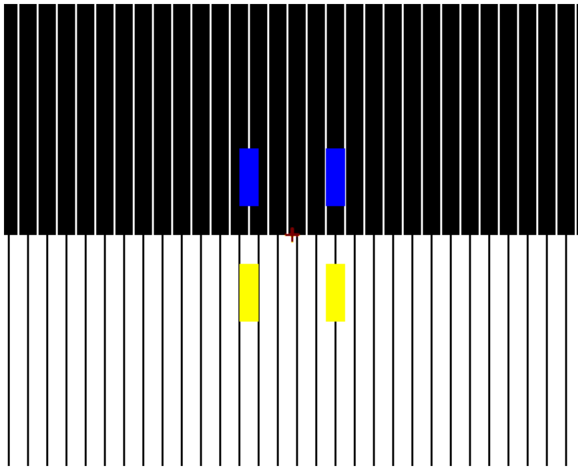
underlying the reverse phi motion and other phenomena (Kitaoka, 2006).

In the kickback illusion, when edges of a blue rectangle pass over pinstripes, the leading blue edge hides a white line and the trailing blue edge uncovers another white line (Movie 25). The former corresponds to the disappearance of the white contours shown in Movie 32, while the latter corresponds to the appearance of the white contours. The same is true for the yellow one. The direction of this illusory motion is opposite to that of the moving edges and the backward motion is observed in the kickback illusion.

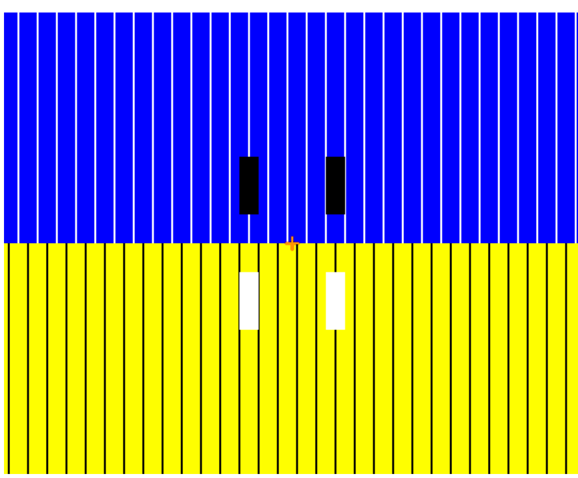
In the kick-forward illusion, when edges of a black rectangle pass over pinstripes, the leading black edge hides a white line and the trailing black edge uncovers another white line (Movie 28). The former corresponds to the disappearance of the white contours shown in Movie 32, while the latter corresponds to the appearance of the white contours. The same is true for the yellow one. The direction of this illusory motion is the same as that of the moving edges, and the acceleration of motion is observed in the kick-forward illusion.

The driving-on-a-bumpy-road illusion

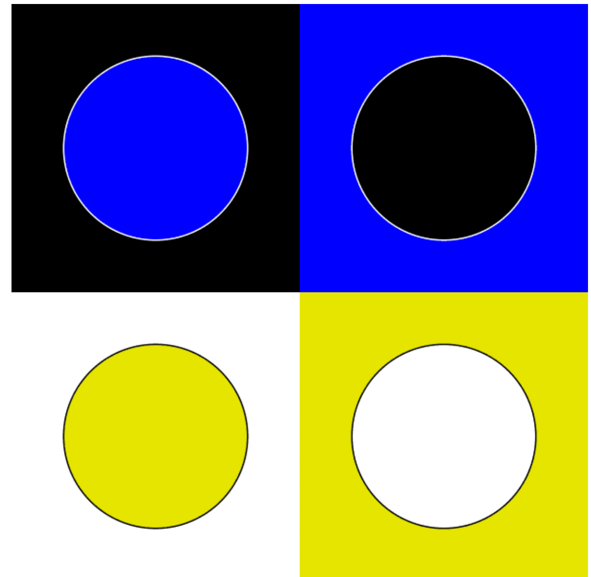
Movie 33 shows an instance in which blue rectangles move across a grating made up of black pinstripes on a white background, while yellow rectangles move across a grating of white pinstripes on a black background. The spacing of two adjacent pinstripes is the same as the width of each rectangle. When the edges of rectangles pass over pinstripes, the rectangles appear to be captured by the



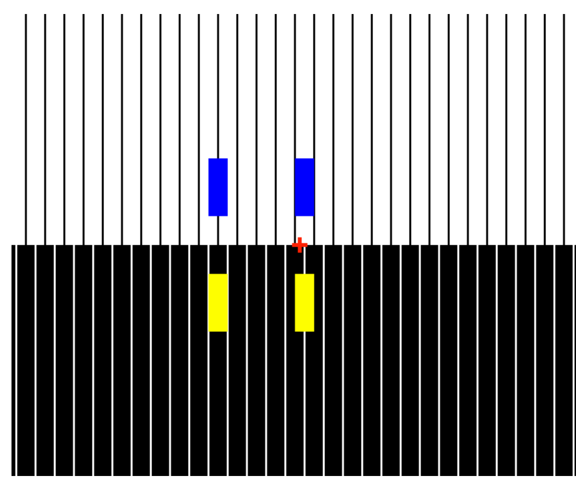
Movie 30. A demonstration of the inverted variant of the kickback illusion. Blue or yellow rectangles (20 pixels wide) are stationary, and a grating made up of white or black pinstripes (2 pixels wide for each pinstripe; inter-pinstripe spacing: 20 pixels) on black or white backgrounds, respectively, move rightward at a constant speed (1 pixel / 30 ms). The rectangles appear to jump in the same direction as the moving grating.



Movie 31. A demonstration of the inverted variant of the kick-forward illusion. Black or white rectangles (20 pixels wide) are stationary, and a grating made up of white or black pinstripes (2 pixels wide for each pinstripe; inter-pinstripe spacing: 20 pixels) on blue or yellow backgrounds, respectively, moves rightward at a constant speed (1 pixel / 30 ms) behind the rectangles. The rectangles appear to jump in the opposite direction from the moving grating.



Movie 32. A demonstration of the luminance-change-dependent motion illusion underlying the 'kick' part of the kickback illusion, the kick-forward one, and their inverted variants. Disks appear to expand or contract when their circumference contours appear or disappear, although each disk does not change in size. For details, see the text.



Movie 33. A demonstration of the driving-on-a-bumpy-road illusion. Blue or yellow rectangles (20 pixels wide) move horizontally back and forth at a constant speed (1 pixel / 60 ms) in front of a grating made up of black or white pinstripes (2 pixels wide for each pinstripe; inter-pinstripe spacing: 20 pixels) on white or black backgrounds, respectively. Rectangles appear to slow down when their edges pass over them.

pinstripes, although Howe et al. (2006, their Stimulus 7c demo) reported 'a percept of almost completely smooth motion'. The whole appearance is something like running a car on a bumpy road. Movie 34 shows the inverted variant, in which stationary rectangles appear to be captured by moving pinstripes and to move with them when pinstripes pass over both edges of a rectangle. Different from the dramatic difference between the kickback illusion and the kick-forward illusion, the appearance does not change even if the colors are exchanged so that

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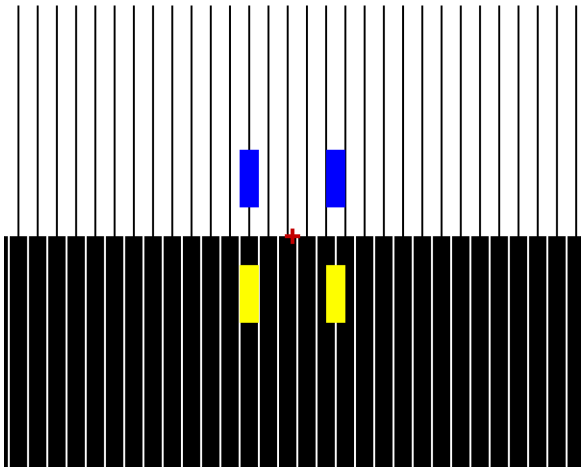
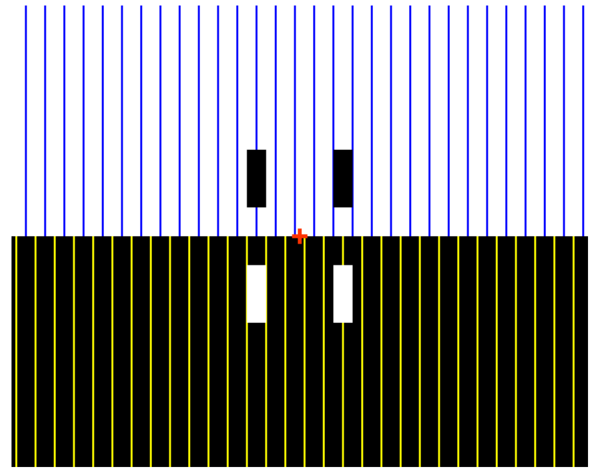
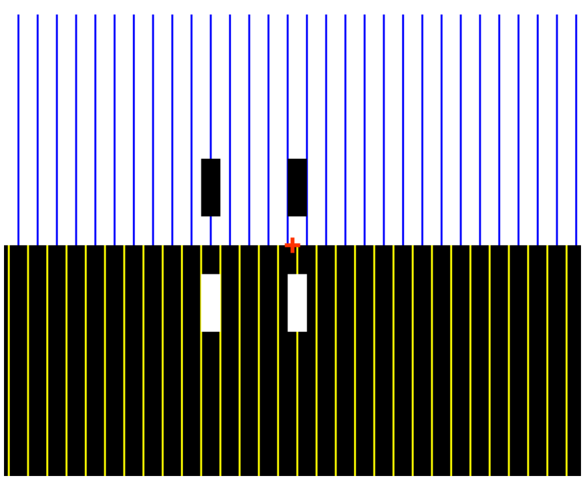


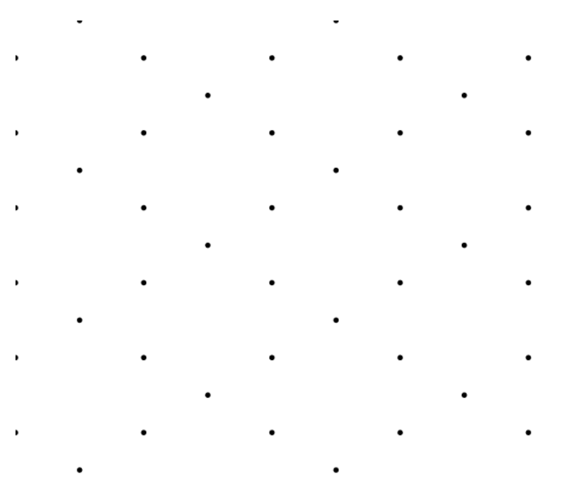
Movie 34. A demonstration of the inverted variant of the driving-on-a-bumpy-road illusion. Blue or yellow rectangles (20 pixels wide) are stationary and a grating made up of black or white pinstripes (2 pixels wide for each pinstripe; inter-pinstripe spacing: 20 pixels) on white or black backgrounds, respectively, move rightward at a constant speed (1 pixel / 50 ms) behind the rectangles. The rectangles appear to be captured by the moving grating and move with it when pinstripes pass under their edges.



Movie 36. Another demonstration of the inverted variant of the driving-on-a-bumpy-road illusion. Black or white rectangles (20 pixels wide) are stationary, and a grating made up of blue and yellow pinstripes (2 pixels wide for each pinstripe; inter-pinstripe spacing: 20 pixels) on white or black backgrounds, respectively, move rightward at a constant speed (1 pixel / 50 ms) behind the rectangles. The rectangles appear to be captured by the moving grating and move with it when pinstripes pass under their edges.



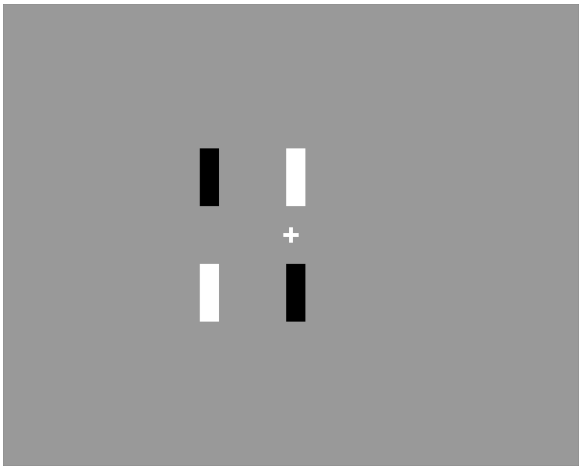
Movie 35. Another demonstration of the driving-on-a-bumpy-road illusion. Black or white rectangles (20 pixels wide) move horizontally back and forth at a constant speed (1 pixel / 60 ms) in front of a grating made up of blue or yellow pinstripes (2 pixels wide for each pinstripe; inter-pinstripe spacing: 20 pixels) on white or black backgrounds, respectively. Rectangles appear to slow down when their edges pass over them.



Movie 37. A demonstration of the pausing-and-sticking illusion. Moving dots appear to pause when they cross each other. Note that this effect is observed when moving dots appear to stream.

rectangles are black or white and pinstripes are blue or yellow (Movies 35 and 36).

It is suggested that the extinction effect occurs when edges pass over pinstripes because they are of low contrast and the position capture or motion capture are followed. Moreover, one may point out a resemblance to the pausing-and-sticking illusion (Goldberg & Pomerantz, 1982), a phenomenon that moving objects appear to pause when they cross each other (Movie 37). Yet, there is a large difference in condition. The pausing-and-sticking illusion is observed when fast moving objects collide, whereas the running-on-a-bumpy-road illusion is observed when



Movie 38. A demonstration of the footsteps illusion based upon reverse phi motion. Flickering rectangles (20 pixels wide) whose color alternates between black and white move horizontally back and forth at a constant speed (2 pixel / 140 ms on average) in front of a homogeneously gray background. They appear to speed up when they are in phi motion while they appear to slow down when they are in reverse phi motion. In this movie, two of the rectangles started with the phase of phi motion (see Fig. 14), and 1,400 ms later they switch to the phase of reverse phi motion. Conversely, the other two rectangles started with the phase of reverse phi motion, and 1,400 ms later, they switch to the phase of phi motion.

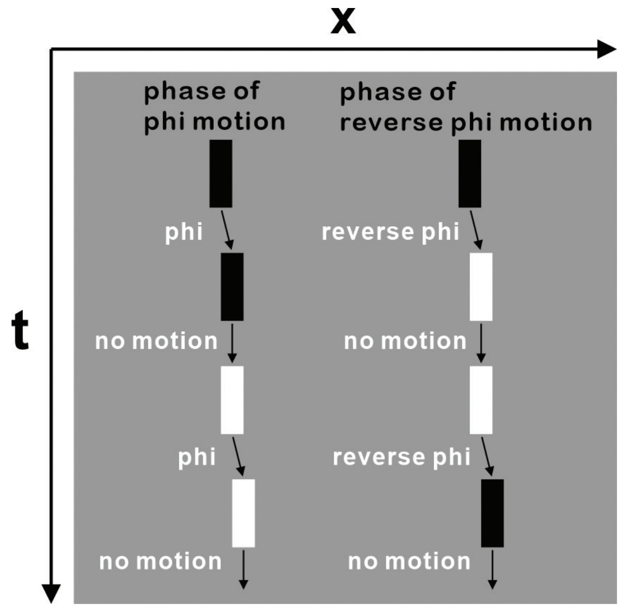


Fig. 14. The phase of phi motion and that of reverse phi motion installed in Movie 38. One phase consists of a repetition of four frames (70 ms for each). Rectangles move 1 pixel from the first frame to the second one. They stay there from the second to the third. They move 1 pixel from the third to the fourth. They stay there from the fourth frame back to the first one of the next phase. For phi motion, contrast polarity does not change when rectangles move, whereas it changes while they stay there. Inversely, for reverse phi motion, contrast polarity changes when rectangles move, whereas it does not change while they stay there. The phase of phi motion is repeated five times (1,400 ms), followed by the phase of reverse phi motion that is repeated five times, and vice versa.

moving edges pass over stationary pinstripes. Probably, they are not the same illusion.

The footsteps illusion based upon reverse phi motion

The last one introduced in this article is the footsteps illusion based upon the difference in apparent speed between phi motion and reverse phi motion (Movie 38). Rectangles appear to move fast when they are in phi motion, while they appear to move slowly or move backward when they are in reverse phi motion. Figure 14 shows how to install these phenomena in Movie 38. Phi motion refers to a normal motion perception of an object in which the object appears to move as it does, while reverse phi refers to an illusory motion perception of an object in which the object appears to move in the opposite direction to its positional shift when the contrast polarity of the object is reversed (Anstis, 1970; Anstis & Rogers, 1975, 1986; Rogers et al., 2019). Although this variant resembles the original footsteps illusion in appearance, the mechanisms between them are quite different.

Rating of the footsteps illusion and its variants

To confirm the described phenomenal observations on the footsteps illusion and its variants, the degree of 'footstep appearance' in each movie was rated by seven observers. First, each of the observers regarded Movie 1 that shows the standard footsteps illusion as the reference stimulus that should be rated '10'. A rating of '0' indicates completely smooth motion. A rating of more than '10' was allowed. Observers rated twenty-seven movies (Movies 1–3, 5, 6, 10–14, 17–25, 28, 30, 31, 33–36, and 38) listed in Table 1. Since this study was conducted in the period of the coronavirus lockdown in 2020, the first author asked observers to rate them on their individual displays. The size of the movie (600 × 480 pixels) shown on each display and the viewing distance were recorded. The results are shown in Fig. 15, which confirms these illusions. Moreover, it was confirmed that the railroad-track variant (Movie 17) is as strong as the footsteps illusion (Anstis, 2004), while the clearing-in-a-forest variant (Movie 18) shows little or no footsteps illusion (Anstis, 2004).

List of the geometrical illusion involved in the footsteps illusion and its variants

Although the involvement of a geometrical illusion in the footsteps illusion has been pointed out (Sunaga et al., 2008; Thompson & Anstis, 2005), we think this geometrical illusion is a variant of the 'static displacements' proposed by

Table 1. A list of the twenty-seven movies that were rated for the degree of footstep appearance

Movie	Variants (mean ratings)
1	Footsteps illusion (10)
2	Achromatic footsteps illusion (dark-gray or light-gray rectangles) (10.7)
3	Achromatic footsteps illusion (black or white rectangles) (7.1)
5	Inverted variant of the footsteps illusion (Movie 1) (6.7)
6	Footsteps illusion without fine stripes (1.2)
10	Achromatic footsteps illusion (black or white rectangles and stripes) (11.9)
11	Inverted variant of the achromatic footsteps illusion (Movie 10) (9.0)
12	Horizontally elongated variant (2.2)
13	Enhanced version of the horizontally elongated variant (10.7)
14	Inverted variant of the enhanced version of the horizontally elongated variant (Movie 13) (5.9)
17	Rail-track variant (8.6)
18	Clearing-in-a-forest variant (0.1)
19	Color-based variant (3.6)
20	Inverted variant of the color-based variant (Movie 19) (3.2)
21	Contrast-modulated variant (7.4)
22	Inverted variant of the contrast-modulated variant (Movie 21) (0.6)
23	Offset-based variant (8.1)
24	Inverted variant of the offset-based variant (Movie 23) (5.5)
25	Kickback illusion (11.0)
28	Kick-forward illusion (7.4)
30	Inverted variant of the kickback illusion (Movie 25) (8.8)
31	Inverted variant of the kick-forward illusion (Movie 28) (7.5)
33	Driving-on-a-bumpy-road illusion (3.1)
34	Inverted variant of Movie 33 (2.6)
35	Another demonstration of the driving-on-a-bumpy-road illusion (1.5)
36	Inverted variant of Movie 35 (1.2)
38	Footsteps illusion based upon the reverse phi motion (9.6)

Note: Movie 1 that shows an instance of the standard footsteps illusion served as the reference rated '10'. A rating of '0' was given to the perception of coherent motion as it is. The results are put in parentheses.

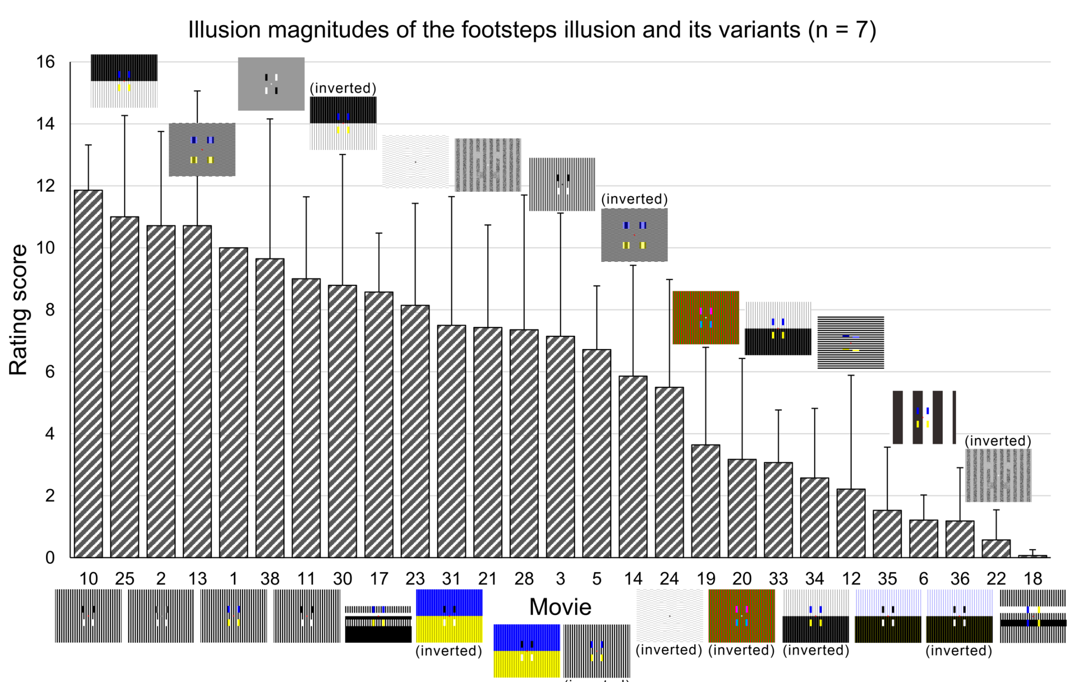


Fig. 15. Mean rating scores and errors (standard deviation [SD]) of the degree of footsteps appearance in the 27 movies.

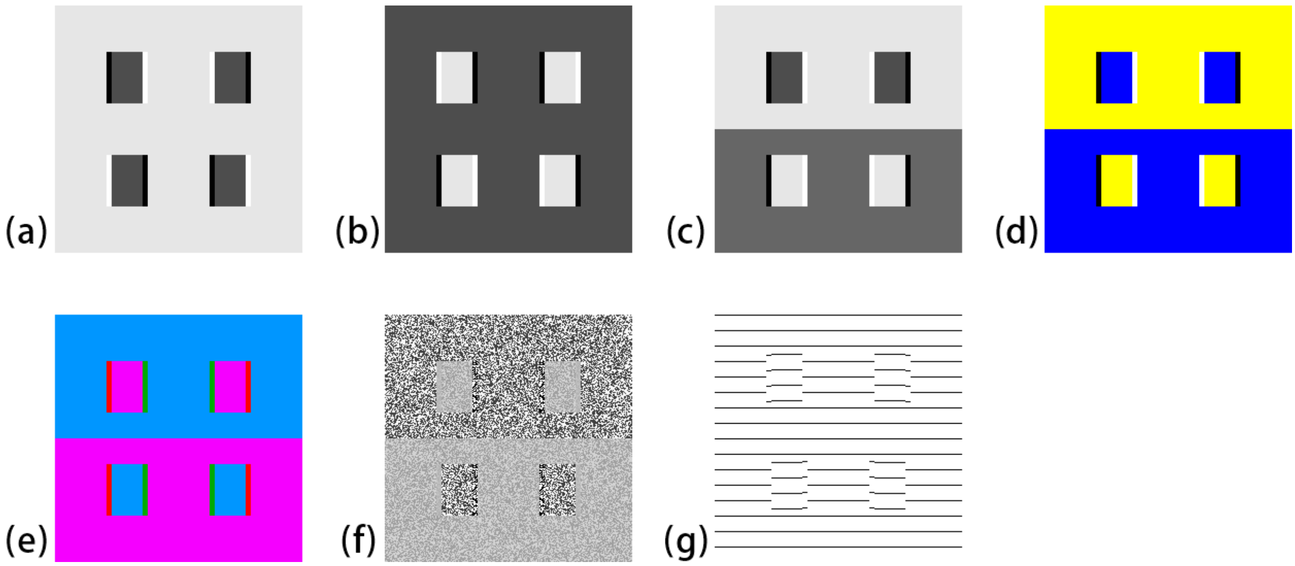


Fig. 16. The geometrical illusions, in which the spacing of the upper two rectangles appears to be larger than that of the lower two, although they are aligned vertically. (a–c) The static displacement illusion proposed by Gregory and Heard (1983). (d) A variant of the static displacement illusion corresponding to the geometrical illusion observed in the footsteps illusion. (e) A variant corresponding to the geometrical illusion observed in the color-based footsteps illusion. (f) A variant corresponding to the geometrical illusion observed in the contrast-modulated footsteps illusion. (g) A variant corresponding to the geometrical illusion observed in the offset-based footsteps illusion.

Gregory and Heard (1983). Figure 16a consists of four dark rectangles in front of a light-gray background. Each rectangle is flanked by black or white line segment at the lateral sides. This image shows a geometrical illusion that the spacing of the rectangles in the upper row appear to be larger than that of the rectangles in the lower row, although they are aligned vertically. When the gray of rectangles is exchanged with that of the background and black or light flanks are exchanged with each other, the upper spacing appears to be larger than the lower (Fig. 16b). The position of a dark rectangle appears to shift toward its black flank and away from its white one, while the position of a light rectangle appears to shift toward its white flank and away from its dark flank. Figure 16c is a combined image in which the spacing of the upper dark-gray rectangles appears to be larger than that of the lower light-gray ones. Even if, in Fig. 16c, the dark-gray is exchanged with blue and the light-gray is replaced with yellow, the illusion does not change (Fig. 16d). The spacing of the upper blue rectangles appears to be larger than that of the lower yellow ones. The geometrical illusion shown in this figure just corresponds to the illusion shown in Fig. 2a.

Moreover, even if the dark-gray, light-gray, black, and the white in Fig. 16c are exchanged with the magenta, cyan, red, and the green that are adopted in the color-based footsteps illusion (Movie 19), respectively, the illusion does not change. The spacing of the upper magenta rectangles appears to be larger than that of the lower cyan ones (Fig. 16e). The position of a colored rectangle appears to shift toward the flank of the similar color and away from the flank of the different color. The geometrical illusion shown in this figure just corresponds to the illusion shown in Fig. 10a.

Furthermore, even if the black, dark-gray, light-gray, and white in Fig. 16c are exchanged with random-dot patterns of the lowest, second-lowest, second-highest, and highest contrast that are adopted in the contrast-modulated footsteps illusion (Movie 21), respectively, the illusion does not change. The spacing of the upper low-contrast rectangles appears to be larger than that of the lower high-contrast ones (Fig. 16f). The position of a low-contrast rectangle appears to shift toward its lowest-contrast flank and away from its highest-contrast one, while the position of high-contrast rectangle appears to shift toward its highest-contrast flank and away from its lowest-contrast one. The geometrical illusion shown in this figure just corresponds to that in Fig. 11a.

Figure 16g shows the geometrical illusion corresponding to the offset-based footsteps illusion (Movie 23 and Fig. 12a). The position of a rectangle appears to shift toward its flank with a small offset.

We suggest that the geometrical illusion is involved in some but not all examples of the footsteps illusion. For example, the footsteps illusion based upon the difference in apparent speed depending on edge contrast (Anstis, 2003) (Movie 6) or the enhanced version of the horizontally elongated variant (Movie 13 and Fig. 9) do not show the geometrical illusion.

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Classification of the footsteps illusion and its variants

This article described the footsteps illusion and its abundant variants. It is thought that the illusions collected in this article are not based on a single mechanism. There are at least three groups in regard to supposed underlying mechanisms (Fig. 17). The first group includes the original footsteps illusion, its variants, and their inverted illusions (Movies 1–24). The second one contains the kickback illusion and kick-forward illusion and their variants (Movies 25–31, 33–36). The third one shows the footsteps illusion based upon reverse phi motion (Movie 38). Moreover, the first group can be classified into subgroups depending on the dimension of edge contrast: luminance-contrast type (Movies 1–18), color-contrast one (Movies 19 and 20), modulated-contrast one (Movies 21 and 22), or offset-contrast one (Movies 23 and 24).

For the first group, it is suggested that the footsteps illusion and its variants be attributed to the geometrical illusion or the extinction effect in addition to the difference in perceived speed depending on edge contrast. This suggestion is consistent with Howe et al. (2006) who attributed the footsteps illusion to the motion signals originating from (1) the moving edges, (2) the lateral edges (the upper and lower edges), and (3) the background edges in the vicinity of the moving edge. It is postulated that the geometrical illusion depends on the combination between (1) and (3), the extinction effect is rendered by the combination between (1) and (2) or between (1) and (3), and the difference in perceived speed depending on edge contrast is solely based upon (1).

For the second group, it is suggested that motion illusion triggered by local luminance changes (Movie 32) (Kitaoka, 2006) should play an important part in acceleration or deceleration of moving rectangles. For the third group, a special combination of reverse phi (Anstis, 1970) and phi motion presents a new demonstration of the footsteps illusion.

Conclusion

A common misconception is that when the mechanism is different, the phenomenon is also necessarily different. Conversely, we tend to think that if the phenomenon is similar, the mechanism is also similar. However, it may well be that the phenomena look similar but have different mechanisms. Therefore, it is important to have a proper understanding of phenomena.

This article collated a variety of illusions to be included in a single category or a single phenomenon called 'footsteps illusion', although they are not claimed to be based on a single mechanism. We think that this phenomenal categorization matches the aims of *Journal of Illusion* that focus on phenomenal aspects of perception. We believe that this review can, in the future, help us better understand how motion perception is achieved.

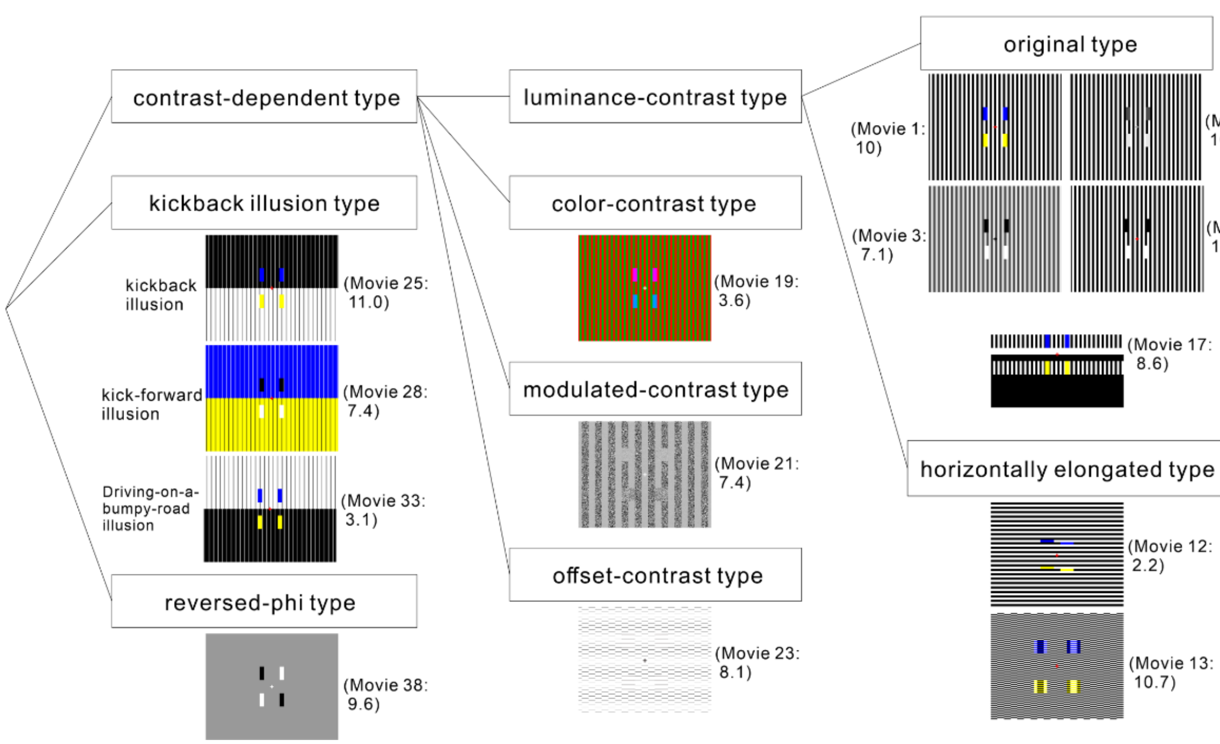

Fig. 17. A tree diagram of a classification of the illusions reviewed in this article. Movie numbers and ratings scores are put in parentheses.

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