Vision Research 133 (2017) 87–94

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Robust size illusion produced by expanding and contracting flow fields

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ARTICLE INFO

Article history:
Received 16 August 2016
Received in revised form 1 January 2017
Accepted 2 January 2017
Available online 27 February 2017

Keywords:
Size illusion
Motion
Optic flow
Size constancy
Depth perception

ABSTRACT

A new illusion is described. Randomly positioned dots moved radially within an imaginary annular window. The dots' motion periodically changed the direction, leading to an alternating percept of expanding and contracting motion. Strikingly, the apparent size of the enclosed circular region shrank during the dots' expanding phases and dilated during the contracting phases. We quantitatively measured the illusion, and found that the presence of energy at the local kinetic edge could not account for the illusion. Besides, we reproduced the illusion on a natural scene background seen from a first-person point of view that moved forward and backward periodically. Blurring the boundaries of motion areas could not reverse the illusion in all subjects. Taken together, our observed illusion is likely induced by optic flow processing with some components of motion contrast. Expanding or contracting dots may induce the self-motion perception of either approaching or leaving way from the circle. These will make the circle appear smaller or larger since its retinal size remains constant.

1. Introduction

Investigations on visual illusions demonstrate that perception does not necessarily correspond to the physical stimulus properties such as orientation (Cavanagh & Anstis, 2013), size (Rock & Kaufman, 1962) and position (Ramachandran & Anstis, 1990). For example, the perceived position of a stationary window appears displaced in the direction of the enclosed motion (Ramachandran & Anstis, 1990). This illusion, termed motion-induced position shift (MIPS), has been repeatedly observed in later work (Kohler, Cavanagh, & Tse, 2015; Mather & Pavan, 2009; Whitney et al., 2003).

Here we report a reversed illusion that was serendipitously observed (Dong & Bao, 2015). Random black and white dots radially moved within an imaginary annular window centered on a mid-gray background. Their moving direction periodically changed, leading to alternating perception of expanding or contracting motion (see Fig. 2a and c or Video S2). According to the findings in MIPS, one would predict that the circular region within the motion-defined boundary dilates during the "expansion" phases and shrinks during the "contraction" phases. However, we observed the reversed. In four experiments, we quantitatively measured the illusion. Since the illusion corresponds with the perceived size changes of the circular region, we call it "size illusion" for simplicity.

2. General methods

2.1. Subjects

Eight naïve subjects (3 males and 5 females, ages ranging from 20 to 24 years) participated in Experiments 1–2. Eight naïve subjects (4 males and 4 females, ages ranging from 20 to 25 years) participated in Experiments 3. Another fifty naïve subjects (20 males and 30 females, ages ranging from 18 to 27 years) participated in Experiment 4. All of them had normal or corrected-to-normal vision. Experimental procedures were approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences, and informed consent was obtained from all the subjects. The work was carried out in accordance with the Code of Ethics of the World Medical Association.

2.2. Apparatus

Stimuli were generated in MATLAB using PsychToolbox version 3 extensions (Brainard, 1997), and were presented on a Dell P1230 CRT monitor with a resolution of 1024 × 768 pixels and a refresh rate of 85 Hz. Subjects viewed the monitor from a distance of 57 cm in a dark room. A chin-rest was used to help minimize head movement.

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http://dx.doi.org/10.1016/j.visres.2017.01.003
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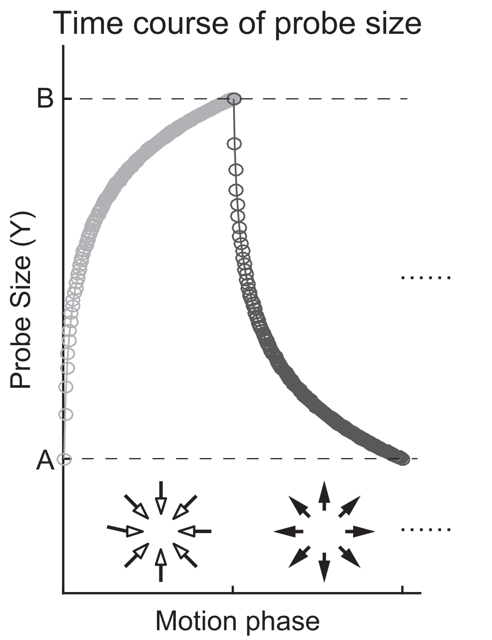

$$Y = A \times N^{(\log B - \log A)/\log N_T} \quad (1)$$

$$Y = A + B - A \times N^{(\log B - \log A)/\log N_T} \quad (2)$$

Fig. 1. The time course of probe size that was simulated with two power functions. Subjects adjusted the minimum and maximum probe size, which correspond to A and B in the equations, to match the perceived size of the central circular region. Then the time course of probe size of each frame during the contraction and expansion phase will be calculated with Eqs. (1) and (2), respectively. Light gray curve represents the probe size during the contracting phase (Eq. (1)), dark gray curve represents the probe size during the expanding phase (Eq. (2)). Open circle denotes the probe size at each frame.

3. Experiments

3.1. Experiment 1

3.1.1. Stimuli and procedures

All the stimuli were displayed on a mid-gray background (45.73 cd/m^2). A black central fixation point (0.1°) was always presented during the experiment. Each frame in a motion sequence consisted of 333 black (0.58 cd/m^2) and 333 white (89.77 cd/m^2) dots (0.15° in diameter) displayed within an imaginary annular window (outer radius: 3°, inner radius: 1.5°) centered on the screen. The dots moved at a speed of 5°/s, whose luminance and initial positions were randomly determined at the beginning of each trial.

In the 24 trials with induction, all the dots moved either towards or away from the fixation point, and changed the direction of motion every 3 s, leading to an alternating percept of expanding or contracting motion. The dots' motion also gave rise to an illusory contour along the inner edge of the imaginary annular window. When viewing such periodic motion in a pilot demo, the authors perceived the illusion that such motion-induced illusory contour dilated during the "contraction" phases and shrank during the "expansion" phases. As a baseline estimation, in another 24 trials, 50% of the dots were randomly selected to move towards the fixation point, while the rest of the dots moved away from it. To examine the role of the contour, we ran additional 24 baseline and induction trials where a black circle was displayed along the inner edge of the imaginary annular window. These four types of trials (see Fig. 2a–c or Video S1–S4 in the Supplemental Material, baseline without physical contour, induction without physical contour, baseline with physical contour, and induction with physical contour) were interleaved randomly throughout the experiment in a counterbalanced order.

Subjects were first asked to complete a questionnaire about their perception during the viewing of a demo of the stimuli. Nobody reported detecting any change of size for the central circular region in the baseline condition, but all reported seeing periodic

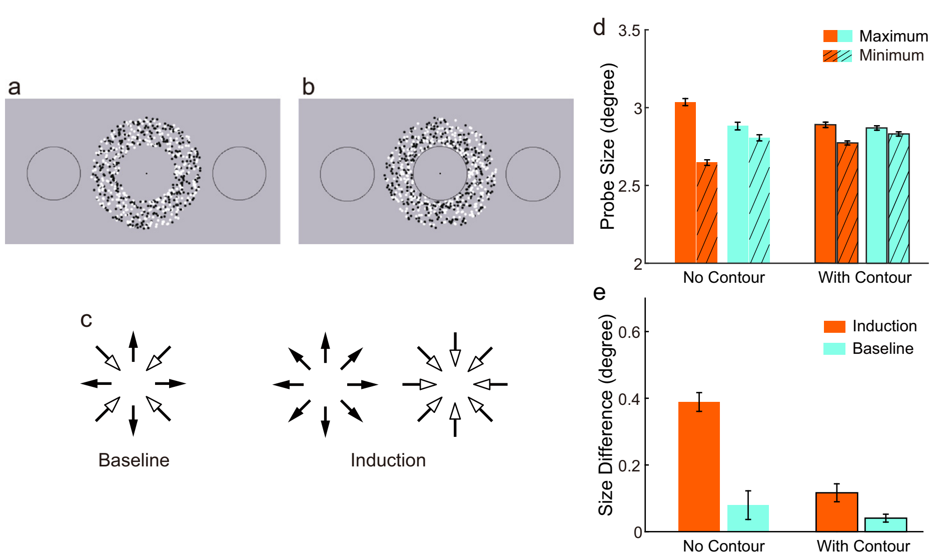

Fig. 2. Stimuli and results of Experiment 1. (a) Stimulus without a physical contour. (b) Stimulus with a physical contour. (c) Two motion patterns. In the baseline trials, 50% of the dots were randomly selected to move towards the fixation point, while the rest of the dots moved away from it. In the induction trials, all the dots moved either towards or away from the fixation point, and changed the direction of motion every 3 s. Subjects were asked to adjust the size of probes, which located on either side of the dot inducer, to match the perceived contour size. (d) The minimum and maximum probe size for the induction trials (orange bars) and baseline trials (cyan bars). Here, "With Contour" stands for the condition with a physical contour along the inner edge of the inducer, while "No Contour" corresponds to the original condition with only the motion-defined higher-order contour. The results for the with contour condition are displayed using bars with black borders. (e) The size difference (i.e. the difference between the minimum and maximum probe size) in the induction (orange bars) and baseline trials (cyan bars) of the "No Contour" and "With Contour" conditions. Error bars represent standard errors of means.

size changes in the induction condition. Subjects then participated in the formal experiment. In each trial, two probe circles were always presented on either side of the fixation point along the horizontal meridian to avoid any bias of size perception at different visual fields. They were centered 5° away from the fixation point, with the initial diameter ranging from 2.92° to 3.08°. Subjects were instructed to view the central gray circle during adjustment without a strict requirement of maintaining central fixation. The task was to adjust the size of the probes to match the perceived size of the central circular region with illusory or physical contour. The periodic change of the probe size was simulated with two power functions to make it synchronous with that of the contour size (see Fig. 1, Eqs. (1) and (2) for the contraction and expansion phase, respectively).

Here, A is the minimum probe size, B is the maximum probe size, N is the index of frames, N_T is the total number of frames of each phase, and Y is the probe size at the Nth frame. Subjects pressed the keys to adjust the maximum and minimum momentary size of the probes. The probe size in each frame was calculated with Eqs. (1) and (2) for the contracting and expanding phases, respectively, with the maximum and minimum probe sizes updated by the subjects' adjustments. A good adjustment could make the time course of the probe size well match that of the contour size, which also empirically validated the equations we used to simulate the time course of the probe size. In the baseline trials, if subjects perceived no size changes, the maximum and minimum probe sizes were required to be adjusted to the same size that matched the perceived size of the central gray region.

3.1.2. Results

Though a small size difference was observed in the baseline trials, a 2 (size difference: maximum size vs. minimum size) × 2 (induction vs. baseline) repeated measurement ANOVA for the condition without physical contour disclosed the significant main effect of size difference ($F(1,7) = 65.99$, $p < 0.001$) and a significant interaction ($F(1,7) = 60.32$, $p < 0.001$), suggesting that the size difference was larger in the induction trials than in the baseline trials (see Fig. 2d). The main effect of induction vs. baseline was not significant ($F(1,7) = 0.05$, $p = 0.825$). Similar results were observed for the condition with contour (main effect of size difference: $F(1,7) = 30.88$, $p < 0.001$, induction vs. baseline: $F(1,7) = 2.68$, $p = 0.146$, interaction: $F(1,7) = 6.65$, $p = 0.037$). Specifically, the size difference reached 0.389 ± 0.080° (no contour) and 0.117 ± 0.076° (with contour) for the induction trials, but only 0.075 ± 0.115° (no contour) and 0.038 ± 0.032° (with contour) for the baseline trials. We then calculated the magnitude of the size illusion by subtracting the size difference in the baseline trials from that in the induction trials. Comparison of the magnitude between the conditions of with and without a physical contour indicated that the size illusion was weaker when a black circle was added along the inner edge of the annulus ($t(7) = 3.62$, $p = 0.009$. See the larger difference of the bars in the 'No contour' condition than in the 'With Contour' condition in Fig. 2e.).

3.2. Experiment 2

The expanding and contracting motion conveys strong optic flow information. Therefore, the illusion might depend upon a global percept of motion. Or it might be simply ascribed to the presence of energy at the local kinetic edge. To examine the local and global accounts, we divided the annulus in half and rendered the dots within each half annulus to move in opposite directions. The local account predicts that this should cause the two halves of the circle defining the annulus' inner edge to appear different sizes, which would cause perceptual distortion of the central circular region. Since the new inducer is no longer like an optic flow, the global account would evidently not predict the perception in Experiment 1. Instead, it may predict a percept that the center of the stimuli shifts in the opposite direction to the sum of vector of the inducer, which is similar to the illusion observed in Duffy and Wurtz (1993) and Pack and Mingolla (1998)'s studies.

3.2.1. Stimuli and procedures

The stimuli were similar to those in Experiment 1. However, in half of the induction trials, the dots in the upper and lower annulus always moved in the opposite radial direction (pattern A, see Fig. 3a or Video S5) that also changed after every 3 s. Similar modifications were made on the dots in the left and right annulus in the rest of the induction trials (pattern B, see Fig. 3b or Video S6). Inconsistent with the local account, a distinct illusion was observed that the central circular region moved upward/downward periodically in pattern A and leftward/rightward in pattern B.

All subjects reported in the questionnaire that they perceived such illusory lateral motion after viewing the demos. In the subsequent tests, they were required to adjust the left (up) and right (down) limits of position shift of two probe circles (3° in diameter). Similar to the Experiment 1, two power functions modeled the time course of the probe locations according to the adjusted position range. For pattern A, the probe circles were located on either side of the fixation along the horizontal meridian since the illusory motion of the circle was upward/downward. While for pattern B, the probe circles were located on either side of the vertical meridian to track the leftward/rightward illusory motion of the circle. Baseline trials and trials with physical contours for both motion patterns were also tested in the same way.

3.2.2. Results

Consistent with the prediction of the global account, we observed an illusion that the entire central circular region shifted in the direction opposite to the sum of the vectors for the dots' motion. A 2 (position shift: right (up) position vs. left (down) position) × 2 (induction vs. baseline) repeated measurement ANOVA revealed a main effect of position shift (all $F(1,7)$s > 15, all $ps < 0.01$) and a significant interaction in all conditions (pattern A: no contour, $F(1,7) = 14.50$, $p = 0.007$, with contour, $F(1,7) = 10.44$, $p = 0.015$, pattern B: no contour, $F(1,7) = 25.29$, $p = 0.002$, with contour, $F(1,7) = 16.88$, $p = 0.005$, also see Fig. 3c). No main effects of induction vs. baseline were found (all $F(1,7)$s < 1.2, all $ps > 0.3$) except for the pattern B without contour ($F(1,7) = 8.77$, $p = 0.021$) which might be caused by the adjustment bias. The significant interactions suggested that in all conditions the position shifts were larger in the induction trials than in the baseline trials (position shifts in baseline trials: pattern A: no contour: 0.024 ± 0.031°, with contour: 0.020 ± 0.027°; pattern B: no contour: 0.041 ± 0.034°, with contour: 0.011 ± 0.014°; position shifts in induction trials: pattern A: no contour: 0.201 ± 0.131°, with contour: 0.072 ± 0.049°; pattern B: no contour: 0.243 ± 0.118°, with contour: 0.076 ± 0.052°). Similar to the Experiment 1, a stronger illusion was observed for the conditions without a physical contour than those with a physical contour (pattern A: $t(7) = 2.51$, $p = 0.041$, pattern B: $t(7) = 2.90$, $p = 0.023$, see Fig. 3d).

Therefore, the above results indicated that the illusion in Experiment 1 was due to a global processing of the inducer.

3.3. Experiment 3

3.3.1. Stimuli and procedures

If our observed illusion is related to optic-flow-like induction, a question then arises: Can natural optic flow induce this illusion? To answer this question, we put a gray disk (3° in diameter) on the center of a natural scene background (1024 × 335 pixels, adapted from a documentary film about the Chinese Forbidden City) seen

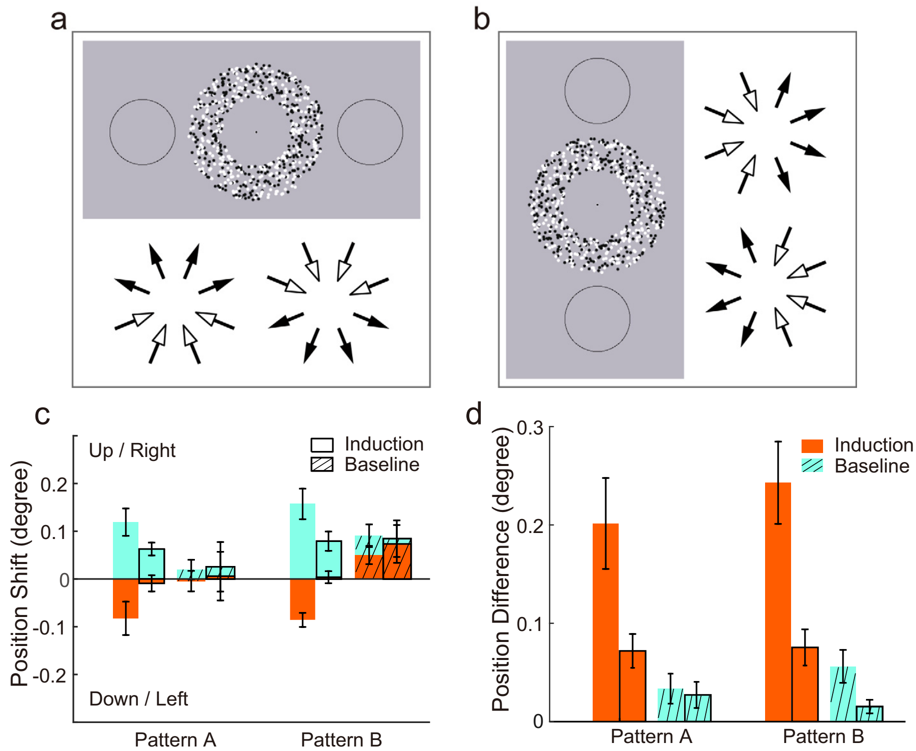

Fig. 3. Stimuli and results of Experiment 2. (a) The stimuli for pattern A in which the dots in the upper and lower annulus always moved in the opposite direction. (b) The stimuli for pattern B in which the dots in the left and right annulus always moved in the opposite direction. (c) The adjusted position shifts for each condition. The bars are positive if the position shifts to the right (upward) of the central gray region, and are negative if the position shifts to the left (downward) of the central gray region. Solid bars represented the results of the induction trials, and bars filled with slashes represented the baseline trials. The results for the with contour condition are displayed using bars with black borders. The right (up) and left (down) limit of position shifts were presented by cyan and orange bars, respectively. (d) The magnitude of position shifts in the induction and baseline trials which were represented by the orange bars and cyan bars filled with slashes respectively. Error bars represent standard errors of means.

from a first-person point of view that moved forward and backward periodically. Interestingly, we observed a similar size illusion. To be more specific, the disk appeared to get smaller when the moving scene indicated a forward movement of the observer which contained expanding optic flow. And the disk appeared to get larger when the observer experienced a backward movement (i.e. contracting optic flow). This was also called the natural type of movie in this experiment (see Fig. 4a or Video S7).

To further test whether natural optic flow could interact with random-dot flow fields (as those used in Experiment 1), in another two movie types, the random-dot flow fields were displayed surrounding the gray disk. The natural optic flow and random-dot flow fields could always move in the same direction, which we called the congruent type (see Video S8). Alternatively, they could always move in the opposite direction, which we called the incongruent type (see Video S9). The semi-period of dots' motion was cut down to 1.76 s (150 frames) due to the limited length of the movie clip. In each trial, two of the three types of movies (Natural, Congruent and Incongruent) were randomly selected and played synchronously on the upper and lower part of the screen, respectively. Each was located 7.5° away from the center of the screen. Subjects were allowed to look at the gray disk in the upper and lower moving background back and forth to compare the magnitude of size change, then made a forced choice in which movie the gray disk changed size more obviously. The movies kept playing until a response was made, which brought the next trial. Totally, there were three trial conditions corresponding to three kinds of comparisons (Congruent vs. Incongruent, Congruent vs. Natural, Incongruent vs. Natural), each including 24 trials.

3.3.2. Results

For each trial condition, we calculated the percentage of trials where subjects reported seeing stronger illusion in the first out of two movie types to be compared. Percentages more than 50% indicated stronger illusion for the first than for the second movie type. In the trials comparing Natural vs. Congruent (see the mid gray bar in Fig. 4b), subjects reported perceiving stronger illusion for the congruent type ($t(7) = 3.46$, $p = 0.011$, one-sample t-test against 50%), indicating that adding a congruent flow fields enhanced the illusion. While in the trials comparing Incongruent vs. either Natural or Congruent, the illusion always appeared weaker for the incongruent type (incongruent vs natural: $t(7) = 21.35$, $p < 0.001$, incongruent vs congruent: $t(7) = 18.41$, $p < 0.001$). This suggested that the incongruent flow fields might counteract the effects induced by the natural optic flow.

3.4. Experiment 4

In the above experiments, we observed an illusion in which the motion-defined boundary moved in the *opposite* direction of the inducing motion. One may argue that this phenomenon seemingly resembles a motion induced illusion called motion contrast. Zhang, Yeh, and De Valois (1993) reported that motion contrast could turn into motion integration (the illusory motion is in the same direction of inducing motion) if the boundary of inducer was blurred. To test whether our illusion is simply a result of motion contrast, in this experiment, we asked subjects to judge whether the illusory motion was in the same (motion integration) or opposite (motion contrast) direction of the inducing motion when the boundary of inducer was either sharp or blurred. If our size illusion simply results from motion contrast, the illusory size changes would be

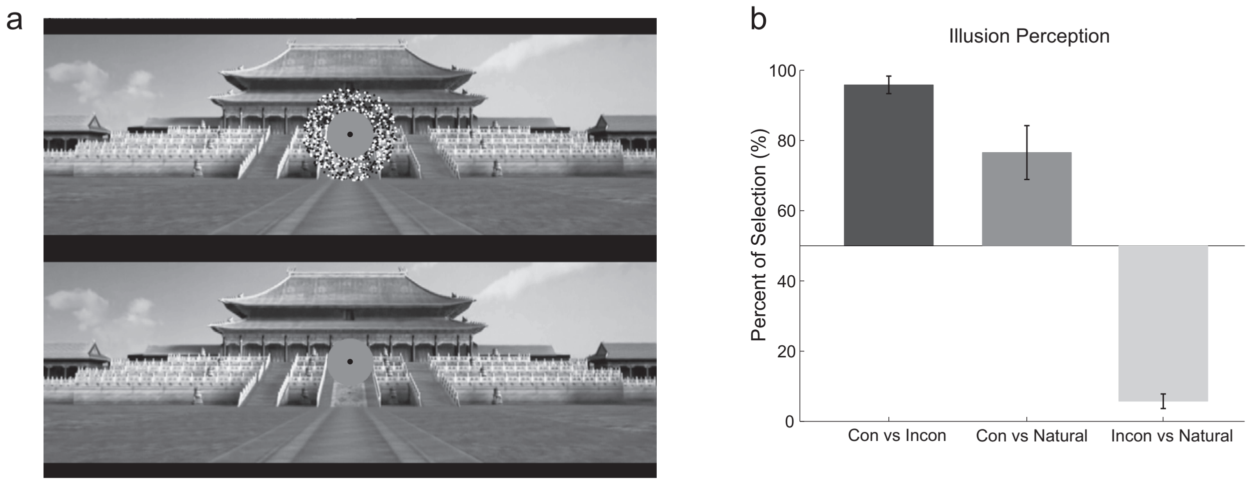

Fig. 4. Stimuli and results of Experiment 3. (a) The stimuli in Experiment 3. In the natural movie type, a gray disk was displayed on the center of a natural scene background that moved forward and backward periodically in a first-person point of view. In the congruent (incongruent) movie type, the superimposing dot inducer moved in the same (opposite) direction as the background. Two movies were displayed in each trial. Subjects were required to make a forced choice in which movie the gray disk changed size more obviously. (b) The percentage of trials where subjects reported seeing stronger illusion in the first out of two movie types to be compared. Percentages more than 50% indicated stronger illusion for the first than for the second movie type. For instance, the dark gray bar showed the percentage that stronger illusion was reported for the congruent movie type when comparing Congruent vs. Incongruent. Here, Con and Incon are the abbreviations for congruent and incongruent. Error bars represent standard errors of means.

in the same direction of the inducing motion when the boundary of inducer is blurred. If our size illusion is instead more related to the processing of optic flow, then blurring the boundary of our optic-flow-like inducer may have relatively weaker effects on reversing the direction of the size illusion than blurring the boundary of a non-optic-flow inducer.

3.4.1. Stimuli and procedures

In the following experiment, the size illusion was tested with two different inducers, our optic-flow-like inducer and a non-optic-flow inducer. Each inducer was tested for the sharp and blurry boundary conditions (see Video S10–S15). Thus there were four kinds of motion stimuli, and each kind of stimuli were tested in separate blocks. In the block for optic-flow-like inducer with sharp boundary, dots moved radially in an annular window and the stimulus was similar to that in Experiment 1. The motion direction of dots reversed every 3 s (i.e. 6 s per cycle). In each trial, the moving dots were presented for 5 cycles. In the first 3 cycles, subjects passively viewed the dot motion without making any responses. A beep at the beginning of the fourth cycle cued the subjects to make the responses during the fourth and fifth cycles. Subjects were forced to press either the up-arrow or down-arrow key to indicate whether the perceived size of the central gray disk became larger or smaller in each half cycle. We called this condition the induction condition since according to the results of Experiment 1, subjects could consistently perceive illusory size changes in this condition. Besides, a "baseline" condition was tested where half of the dots moved randomly while the other half moved either to the left or to the right. The task was the same as that for induction trials. Similar stimuli and task were used in the block for optic-flow-like inducer with blurry boundaries except that the boundary of the annulus window was blurred using a Gaussian envelope.

In the other two blocks for non-optic-flow inducers, we used translational moving dots (see Fig. 5a). The dots moved within two rectangular areas ($1.5° \times 6°$) which located 3° to the left and right of central fixation. The boundaries of these areas were either sharp or blurred using a Gaussian envelope. Trials in each block also included an induction condition and a baseline condition. In the induction condition, dots in the two areas moved towards or away from each other. In the baseline condition, half of the dots in the two areas moved randomly and the other half moved in the same direction, either to the left or to the right. In both conditions, the direction of dots motion changed every 3 s for 5 cycles. Subjects performed the 2AFC task to judge whether the distance between two dots areas became larger or smaller in the fourth and fifth cycles.

Totally all subjects finished four blocks of test in this experiment, each block contained 15 baseline trials and 30 induction trials. In case the perceptual experience of the illusion biased the responses, testing sequence for the sharp or blurred conditions was counter-balanced across subjects.

3.4.2. Results

In the baseline conditions, all subjects subjectively reported that they perceived no size changes or distance changes. In agreement with this, the proportion of responses where subjects perceived a change of size or distance in the opposite direction of motion showed no significant difference from the chance level (50%) for both the annular (blurred condition: $t(49) = 0.31$, $p = 0.754$; sharp condition: $t(49) = 0.58$, $p = 0.567$, see Fig. 5b) and rectangular window (blurred condition: $t(49) = 0.73$, $p = 0.472$; sharp condition: $t(49) = 1.53$, $p = 0.133$, see Fig. 5c).

In the induction conditions, the proportion of responses for seeing the size changes in the opposite direction of motion were significantly above the chance level when dots moved in a sharp annular window ($t(49) = 40.32$, $p < 0.001$), suggesting that the subjects predominantly perceived the size changes in the opposite direction of motion. As shown in Fig. 5b, the proportions for all except 3 subjects were above 75%. When the boundaries were blurred, the proportion of responses for seeing the size changes in the opposite direction of motion was still higher than the chance level ($t(49) = 2.51$, $p = 0.015$), however, the distribution of results was different from that in the sharp condition, 23 subjects reported seeing the same size illusion in more than 75% of responses. 19 of them found it was relatively hard to judge the size change, and their proportions fell in between 25% and 75%. 8 subjects predominantly perceived a reversed size illusion that the size of central gray disk changed in the same direction of dots motion, an indication of motion integration.

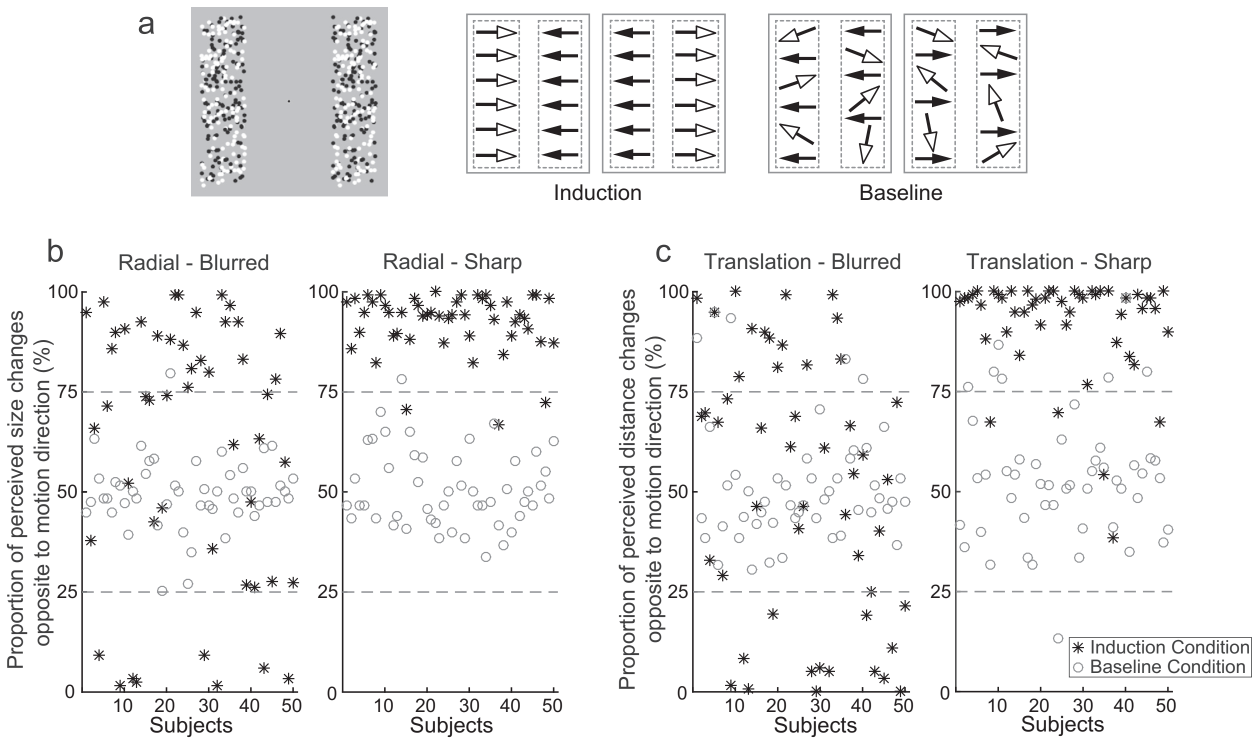

Fig. 5. Stimuli and results of Experiment 4. (a) The stimuli and motion patterns in sharp condition that dots moved translationally. Arrows indicated motion directions. (b) The proportion of responses that the perceived size changed in the opposite direction of dots motion when dots moved radially in an annular window with either sharp or blurry boundary. (c) The proportion of responses that the perceived distance changed in the opposite direction of dots motion when dots moved translationally in two rectangle areas with either sharp or blurry boundary. '*' represents the induction condition, '○' represents baseline condition, gray dashed lines denote the proportion of 25% and 75%.

For the rectangular inducers (see Fig. 5c), the edge blurring of the window showed a stronger effect to turn motion contrast into motion integration. When the boundaries were sharp, the analysis of proportion of responses suggested that the subjects mainly perceived distance changes in the opposite direction of motion ($t(49) = 23.26$, $p < 0.001$, against the chance level). The proportions for all except 5 subjects were above 75%. While when the boundaries were blurred, only 14 subjects reported seeing the distance changes in the opposite direction of motion in more than 75% of responses. 14 subjects found a reversed illusion that the distance between two areas changed in the same direction of dots motion (proportions were less than 25%), indicating the perception of motion integration. The other 22 of the subjects had mixed perceptions.

A 2 (inducer: radial vs. translational) × 2 (boundary: sharp vs. blurred) repeated measurement ANOVA on the proportion of judgement revealed a significant main effect of inducer ($F(1,49) = 7.34$, $p = 0.009$) and boundary ($F(1,49) = 58.94$, $p < 0.001$), as well as a significant interaction between them ($F(1,49) = 7.16$, $p = 0.010$), suggesting that blurring the boundaries may have different effects on the perceptual differences caused by the two inducers. We then calculated the differences of the proportions between the sharp and blurred blocks for the two different kinds of inducers, and found that blurring the boundaries of the windows led to a significant stronger reduction of the proportion values for the non-optic-flow inducer than for the optic-flow-like inducer ($t(49) = 2.68$, $p = 0.010$). These results indicated that, to some extents, blurring the boundaries of the inducers could reverse the illusion, just like how blurring edges turns motion contrast into motion integration (Zhang et al., 1993). If motion contrast is the unique mechanism driving the illusion in the sharp conditions, one would expect identical outcomes led by blurring the boundaries of the inducers. However, if the mechanisms processing optic flow information jointly contribute to the illusion in the sharp conditions, their effects should not be strongly affected by the edge blur of the inducers. Accordingly, one may expect that blurring the boundaries of the inducers should have relatively weak effects in reversing the direction of the size illusion. And the results in Experiment 4 indeed agree with this latter expectation, suggesting that our observed size illusion may be predominantly contributed by the mechanisms for optic flow processing, though motion contrast also makes certain contributions to it.

4. Discussion

A new motion-induced illusion was reported. Contrary to the MIPS, here the motion-defined boundary moved in the *opposite* direction of the inducing motion within the physically stationary window. Using a series of experiments, we find that the size illusion arises from global processing of the inducer. It may occur at higher level processing stages where receptive fields of neurons are large. Our results suggest that the size illusion can be induced by natural flow patterns; it can be perceived in both fovea and periphery (discussed below); and the illusion induced by radial flow patterns is different from that induced by translational motion patterns. All the features of the illusion consistently show a possible role of optic flow patterns in generating the size illusion.

Previous studies have disclosed that optic flow provides rich information about self-motion (for review, see Britten, 2008). Humans can use optic flow to estimate heading (Dyre & Andersen, 1997; Gibson, 1950), ego-acceleration (Festl, Recktenwald, Yuan, & Mallot, 2012) and travel distance (Frenz & Lappe, 2005). Furthermore, the optical expansion and contraction patterns are effective stimuli for perceived motion in depth

(Regan & Beverley, 1978; Swanston & Gogel, 1986). In a view of optic flow account, our illusion might be a part of the size illusion family that the stimuli with the same retinal visual angle can appear to have very different sizes when perceived to be at different distances (Murray, Boyaci, & Kersten, 2006; Song, Schwarzkopf, & Rees, 2011). This connection to size illusions depends on an assumption of feeling of self-motion. In our paradigms, the "expansion" or "contraction" phases may make the observers feel like approaching or leaving away from the screen, respectively, leaving the retinal visual angle of the motion-defined contour constant. Thus, the circular region appears larger when the observers feel leaving away from the screen ("contraction" phases), or smaller when the observers feel approaching to the screen ("expansion" phases). By using a natural scene background, our Experiment 3 reproduced this illusion under the induction of natural optic flow. One may argue that the illusion could be driven by the size contrast between the disk and background objects. However, this does not contradict the view of size constancy in depth, since motion-in-depth in a natural scene is always accompanied by the changes of objects' retinal sizes. An alternative account for the results in Experiment 3 is that the integration of local signals of the overlapped area strengthened or counteracted the original size illusion induced by the natural optic flow. Further experiments are needed to test which account is more likely.

It should be noted that Qian and Petrov (2012) report a size illusion (StarTrek), which is also induced by optic flow stimuli. However, there are clear differences between them. The StarTrek illusion is observed on the physical objects moving in real depth, while ours occurs on a display region surrounded by 2D optic flow fields. Furthermore, the StarTrek illusion includes a contrast illusion component that is twice stronger than its size illusion component. However, no changes of perceived contrast were observed in our experiments.

Another related phenomenon is induced motion (for review see Reinhardt-Rutland, 1988), an illusion that a stationary target appears to move in the opposite direction of adjacent coherent motion. However, induction of translational motion has always been used for studying induced motion (Murakami & Shimojo, 1993; Takemura, Ashida, Amano, Kitaoka, & Murakami, 2012). Our inducer instead conveys optic flow information that may involve particular mechanisms underlying perception of heading. Besides, induced motion is preferentially observed at small eccentricity (<5°) and when luminance contrast between the target and screen background is high (Murakami & Shimojo, 1993). Clearly, in our first experiment, the central disk (i.e. "target") and the background were always gray. Therefore, the luminance contrast was zero, which was not optimized for observing induced motion. Importantly, it is found that visual system maintained high sensitivity to vection perception with optic flow in the periphery (Dichgans & Brandt, 1978; Warren & Kurtz, 1992). We then tried displaying our stimuli in the periphery (7°), but found it hard to recognize the kinetic boundary, let alone to detect a size change. Hence, we tried this manipulation on the natural scene background in 6 subjects. The stimuli were the same as in the natural condition of Experiment 3 except that subjects were required to stare at a fixation point displayed 7° away from the center of the natural scene background. All observed robust size illusion. Therefore, the two illusions likely involve different neural mechanisms.

It should be noted that the stimuli in Experiment 4 resemble those in Ramachandran and Anstis (1990)'s study. However, our results are opposite to theirs. In Ramachandran and Anstis (1990)'s experiment, four groups of gray moving dots were presented in four static windows on a black background with sparse gray random dots, with two on the upper visual field and two on the lower visual field. Dots in the upper windows consistently moved toward or away from the vertical meridian, while dots in the lower windows moved in the opposite direction. They found the dots windows seemed closer if dots moved toward the vertical meridian. However, the effect was weakened if the moving dots were presented with no surrounding dots like our study. Considering that only two groups of dots were presented in our experiment, subjects might not be able to compare the illusory position shift induced by different motion directions. Another difference in stimuli is that the motion direction in our work reversed every 3 s within a trial. Based on our observations, the size illusion is most obvious immediately after the motion direction reversed. However, the reversal of motion direction did not occur in Ramachandran and Anstis (1990)'s work. All these differences in stimuli presentation could cause the different illusions in the two studies.

The results of Experiment 4 also disclosed some similarities between our size illusion and motion contrast (integration) that some subjects perceived a reversed illusion if the boundary of inducer was blurred. However, there are still some differences between the two illusions. In Zhang et al. (1993)'s work, drifting grating, which shares little similarity with optic flow, was used as the stimulus. Robust motion integration was observed by all the subjects when the boundary of the stimulus was fuzzy and the pattern was viewed at 2° eccentricity. In our Experiment 4, the dots areas were about 3° away from the central fixation, however, only a few subjects perceived a reversal of the size illusion in the blurred conditions for both the annular and rectangular inducers. As the conclusion of Zhang et al. (1993) was derived from only four subjects, and the complete reversal was not observed in all subjects when the stimuli was presented foveally, our experiment could not completely rule out the contribution of motion contrast/integration. However, the blurring-induced reversal of the size/distance illusion was considerably weaker for the annular inducer than for the rectangular inducer. This result cannot be easily explained by the sole contribution from motion contrast/integration, and suggests that the processing of the radial flow motion is different from the processing of the translation motion stimuli.

Combining all the results, we speculate that the mechanisms processing optic flow information contribute to the size illusion. The corresponding neural substrates may involve the extrastriate and parietal cortices for processing optic flow patterns (Morrone et al., 2000; Pitzalis et al., 2010) and motion-defined contours (Dupont et al., 1997; Larsson, Heeger, & Landy, 2010). However, more direct evidence is still needed to make a stronger conclusion. Moreover, there should be more than one mechanism underlying the present illusion. For example, the illusion seems to be contributed to some extent by motion contrast. Future studies will try to understand the brain mechanisms for this new type of size illusion.

Author contributions

X. Dong, J. Bai and M. Bao designed the research. X. Dong performed the research. X. Dong and M. Bao analyzed the data. X. Dong and M. Bao wrote the paper. All authors approved the final version of the manuscript for submission.

Declaration of conflicting interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Acknowledgments

We thank Shinsuke Shimojo and Stephen Engel for helpful comments. This research was supported by the Key Research Program of Chinese Academy of Sciences (KSZD-EW-TZ-003) and the National Natural Science Foundation of China (31371030).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.visres.2017.01.003.

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