Motion Perception, Psychology of

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CONTENTS

Introduction
Uses of motion information
Motion cues

The motion after-effect
Apparent motion
Induced motion

Motion perception is important for figure–ground segregation, three-dimensional vision, and visual guidance of action. Specialized brain cells detect image motion. Adaptation in these cells leads to illusory motion, such as the motion after-effect.

INTRODUCTION

An essential attribute that distinguishes all animals from plants is their capacity for voluntary movement. Animals move to find mates, shelter, and food, and to avoid being eaten. But the ability to move brings with it the need to sense movement, whether to navigate through the world, or to detect the movement of other mobile animals such as approaching predators. For sighted animals, this means sensing movement in the visual image that is projected into the eye. The image is formed on a sheet of light-sensitive cells that line the inside of the eye – the retina. Specialized neural processes are required to detect the presence of movement in the retinal image.

USES OF MOTION INFORMATION

Surfaces, shapes, and objects in the scene under view create spatial patterns of light and dark in the retinal image. The image is very rarely still, as in a photograph. Instead, it is in a state of continuous change, due to the movement of objects in the scene (e.g. an approaching predator) or to shifts in the position of the observer’s eyes, head, or body (e.g. while running away from the predator). Perception of movement in the image is crucial, because it can be used in a number of ways.

Figure–Ground Segregation

Shapes and objects that are invisible while static (e.g. camouflaged animals) are revealed as soon as they move relative to the background. Many animals have evolved special ways of moving, in an attempt to defeat figure–ground segregation. For example, prey animals such as lizards and rodents move in short, rapid bursts in between periods of complete stillness, in order to minimize the chances of detection by predators. Predators such as cats tend to move slowly and smoothly to avoid being seen by their prey.

Extraction of Three-dimensional Structure

When any solid object moves, the images of its various parts that are cast on the retina move relative to each other. Relative motion of this kind can be used to extract the three-dimensional structure of the object. For example, in a sideways view of a rotating globe, surface markings near the equator move across the field of view more rapidly than markings near the poles. In addition, markings near the equator follow a linear path, whereas those near the poles follow elliptical paths. This highly structured variation in speed and direction is sufficient for the perception of the shape’s three-dimensional structure.

Visual Guidance of Action

As the observer moves about the world, image detail ‘flows’ across the image on their retinas, to create a characteristic motion pattern known as ‘optic flow’. A great deal of information can be extracted from optic flow, including the speed and direction of self-motion. For example, as you run through a wood, looking ahead, image details arising from rocks on the ground, and from trees ahead, appear near the centre of your vision and then flow through your field of view as they disappear behind you, creating an expanding flow field. This pattern of motion flow allows you to navigate a path through the wood without colliding with
trees or misplacing your feet. The powerful movement effects experienced in ‘Imax’ movie theatres are due to optic flow.

**MOTION CUES**

The movement of objects under view, or of the observer through the world, cause the spatial pattern of light and dark in the image to fluctuate over time. For example, if you are looking across a relatively dark room, and a friend wearing light clothing moves across your line of sight, then the amount of light falling in the small region of the image at the centre of your vision will suddenly increase just as the friend intersects your line of sight, and then decrease again once they have passed through. If the room is empty, and you switch on a light, then again the amount of light falling on the image at the centre of your vision will increase. How can the brain distinguish between changes in image intensity due to movement and changes due to other causes, such as changing illumination? In order to solve this problem, the brain must combine information from several places in the image, rather than gathering information from just one place at a time. A change in illumination causes a change in intensity *everywhere* in the image simultaneously, whereas movement causes changes in only a very small part of the image at a time, as Figure 1 demonstrates.

The left-hand and middle panels of Figure 1 show two views of a scene containing a light human figure moving across a dark background. It is difficult to tell what movement has occurred between the two views by inspecting them individually. The right-hand panel in Figure 1 shows the changes in light intensity that took place between the two views. Bright areas correspond to places where intensity increased over time from the first view to the second view, and dark areas correspond to places where intensity decreased from the first view to the second view. Grey areas were unchanged between the two views. Notice that the ‘difference image’ on the right effectively isolates the parts of the scene that contained movement. Stationary features disappear. This would allow the observer to detect the presence of movement, perhaps for figure-ground segregation.

Is it possible to infer the direction in which the figure was moving? Some parts of the scene increased in intensity over time (light in the right-hand panel), and other parts of the scene decreased in intensity over time (dark in the right-hand panel). Increases in intensity occurred where a bright edge belonging to the figure moved rightward into a region of the image that was previously dark (e.g. the shin of the leading leg). Decreases occurred where the edge of the figure moved out of a region of the image, returning that region to darkness (e.g. the calf of the leading leg). The brain can therefore infer the direction of a shape’s movement by finding its edges, and then detecting whether the intensity of the image increases or decreases over time in the region of these edges. Since the 1960s it has been discovered that the brain possesses specialized ‘motion-detecting’ neurons that respond specifically to movement. Each neuron responds only to movement in a specific direction over a small part of the image. Groups of these first-stage neurons are connected to second-stage neurons that integrate information over relatively large areas of the scene, in order to signal the movement of whole shapes and objects.

**THE MOTION AFTER-EFFECT**

The early Greeks were the first to discover a striking visual illusion now known as the motion after-effect (or MAE). The philosopher Aristotle noticed that if he stood in the middle of a river, and directed his gaze down at the fast-flowing water for a short time, when he shifted his gaze towards the riverbank the stationary scene appeared to flow backwards in the opposite direction to the river. This illusion has been rediscovered a number of times, most famously by Thomas Addams, a Scottish scientist, while touring the Scottish Highlands. He visited the Falls of Foyers on the banks of Loch Ness, and noticed that if he fixed his gaze on the falling waters for a short time, and then looked at the rock face beside the falls, the rocks appeared to move upwards for a short time. For this reason the effect is also known as the waterfall illusion. It is powerful, robust, and easily demonstrated. A convenient way to experience the illusion today is to view the title credits of a TV programme or movie. It is important to fix one’s gaze steadily at the centre of the screen rather than track the credits as they roll by. After about 30 seconds of adaptation, subsequently viewed scenes should appear to move in the opposite direction to the credits.

The MAE is thought to arise from adaptation in motion-detecting neurons in the brain, of the kind described in the previous section. While viewing an image containing contours moving in a particular direction, cells ‘tuned’ to respond to that direction will initially respond quite strongly. However, after
prolonged exposure their ability to respond is reduced, and takes some time to recover back to normal levels. Our perception of movement depends on a competition between cells tuned to different directions, rather like a tug-of-war, as shown in Figure 2. Normally, in the presence of a stationary image and without prior exposure to motion, the two opposing teams (‘left’ and ‘right’ in the top row of Figure 2) are well matched at a low level of activity, so we see no motion. While viewing a rightward-moving pattern the ‘right’ team is very active, and easily overcomes the ‘left’ team to win the competition, leading us to see rightward motion (middle panel of Figure 2). Afterwards, the ‘right’ team takes some time to recover, allowing the ‘left’ team to win even while not very active in the presence of a stationary pattern (bottom panel of Figure 2). As a result, illusory motion is seen – the MAE. Once the adapted neurons recover, any bias in favour of one team disappears, so the illusion is no longer seen. Perceptual research on the properties of the MAE indicate that the illusion represents the combined effect of adaptation in at least two populations of cells in the brain, probably corresponding to the first-stage and second-stage motion-detecting neurons described above.

APPARENT MOTION

In natural images of real scenes, moving objects change position in the image in a smooth, continuous manner. If one could inspect the image over shorter and shorter time periods, the shift in position would become smaller and smaller, until at infinitesimally small time intervals, the position shift would also be infinitesimal. For example, the left-hand panel of Figure 3 shows a disk drifting to the right over time. Space is plotted horizontally, and time is plotted vertically. The solid outlines represent the positions of the disk at times 1 and 16. The dashed outlines represent the positions of the disk at intermediate times. For obvious reasons, this kind of movement is called ‘real movement’.

It is also possible to create the perception of movement in an image by changing the position of an object suddenly over a relatively large distance. If one could inspect the image over sufficiently short time periods, there would be no shift in position. For example, the right-hand panel of Figure 3 shows a disk occupying just two discrete positions. As before, the solid outlines represent the positions of the disk at times 1 and 16. The disk shifts position only once, at time 8. So at all other times the disk remains stationary either at the first position or at the second (dashed outlines). Observers do perceive movement in stimuli of this kind – it is the basis for the movement seen in TV and movies. TV images are displayed as a series of static images or frames presented very rapidly (50 frames per second in Europe, 60 frames per second in the USA). Any impression of movement seen in TV images is an illusion created by discrete changes in object position from one frame to the next in the display sequence. This kind of illusory perceived movement is called ‘apparent movement’ or ‘phi movement’, to distinguish it from the real movement seen in natural images. Why is the apparent motion so effective and compelling? A common fallacy is that it results from the ‘persistence of vision’. According to this explanation, each static image persists in our vision for a short time, so that successively presented static images blend together into one apparently continuous scene. However, it is known that visible persistence lasts only about one-tenth of a second, yet apparent motion can be seen between two stationary shapes even when the second shape appears half a second after the first shape has disappeared. Visible persistence may contribute to the perceived smoothness of apparent motion, but it cannot account for the perception of motion itself. The effectiveness of apparent motion stimuli is almost certainly due to their ability to activate motion-detecting neurons in the brain. As described earlier, motion-detecting neurons rely on the systematic changes in image intensity created by a moving object. Apparent motion stimuli also create systematic changes in image intensity. Provided that the parameters of the apparent motion sequence are chosen carefully, it should excite motion-detecting neurons as effectively as real movement. As one would predict from this explanation, good apparent motion is indistinguishable from real movement. Movie and TV animations do seem very smooth and realistic, unless one sits in the very first row in front of a large movie screen. From this position the discontinuity of the movement, particularly in fast action sequences, can be seen easily.

However, responses in motion-detecting neurons are not the only explanation for apparent movement. It has also been argued that we can perceive motion independently of activity in neural detectors, as a result of perceptual inferences or of shifts in attention. According to the perceptual inference theory, apparent motion is the outcome of a perceptual inference to explain the otherwise mysteriously sudden appearance and disappearance of shapes in apparent motion displays. According to the attention-shift theory, apparent motion can also
be perceived when mobile shapes or objects in the image capture and hold the attention of the viewer. As the objects change position in the image, one’s focus of attention shifts to keep track of them. This shift in attention itself gives rise to the perception of apparent motion. Advocates of such high-level processes do not see them as inconsistent with the notion of lower-level neural motion detection, but rather as separate processes that co-exist with low-level detection. It therefore seems likely that the perception of apparent movement is mediated both by low-level processes (motion-detecting neurons) and by high-level processes (inference and attention).

**INDUCED MOTION**

On a cloudy, moonlit night, as relatively large clouds move quickly across the face of the moon, it often seems as if the clouds are stationary but the moon is moving. This illusion is an example of ‘induced motion’: the appearance of motion in a stationary stimulus induced by the physical movement of another stimulus. Generally, induced motion is most effective when a large, slowly moving shape surrounds a smaller, stationary shape, such as the moon surrounded by clouds.

The simplest demonstration of induced motion consists of a small spot surrounded by a large frame, as shown in Figure 4. If the frame moves slowly sideways while the spot remains stationary (left-hand panel), observers tend to perceive the frame as stationary and the spot as moving (right-hand panel). Induced motion highlights the problem of motion attribution. As mentioned earlier, movement in the visual image is detected by specialized motion-detecting neurons. Image motion can arise from two general sources, either movement of objects in the scene under view, or movement of the observer’s body. It is obviously crucial to attribute motion to the correct source, but responses in motion-detecting neurons cannot distinguish between them. The brain appears to use several strategies to solve the problem of motion attribution. These strategies are usually sufficient to arrive at the correct interpretation, but in certain situations the interpretation may be erroneous, leading to illusions such as induced motion. One strategy is to make use of nonvisual information in order to determine whether the observer is moving through the scene. Movement of the eye, head, and body can be established using information from the muscles (or from commands to move the muscles), and from the balance (vestibular) sense. When movement in the image can be accounted for entirely by bodily movement, then no motion is perceived. For example, eye movements create movement in the image. When the eyes turn to the left, the whole image translates to the right on the retina. This translation excites motion-detecting neurons in the brain, yet we do not perceive the world to move. The image motion that results from eye movement is correctly attributed to the eye movement, so no motion is perceived. A second strategy, or heuristic, used in motion attribution relies on assumptions about the nature of the real world. In general, relatively large shapes and objects in a viewed scene tend to remain fixed in position, while small shapes and objects are likely to move. Large areas in a viewed scene may be filled by, for example, the wall of a building or the side of a hill. These shapes are extremely unlikely to move. Small areas, perhaps representing human or animal figures, or vehicles, are very likely to move. Consequently if there is relative movement between a small object and a large surrounding object, then the brain has a tendency to attribute the motion to the small object.

**Further Reading**


**Glossary**

**Balance sense** The sensory system that provides information about the attitude of the body relative to gravitational vertical, and about acceleration of the body through space; its sense organ (vestibular organ) forms part of the inner ear.

**Motion attribution** The perceptual process by which visual movement on the retina is attributed to movement of a particular shape or object in the environment, or to movement of the observer through the environment, or some combination of the two.

**Motion-detecting neuron** A neuron in the central nervous system (in the cortex in primates) that is specialized to respond only to visual stimuli that move across the retina in a particular direction and at a particular speed.

**Optic flow** The expanding pattern of light on the retina that results from relative motion between the observer and the environment (e.g. walking, driving).
Perceptual inference An explanation for perception in which our sensory experience is the outcome of a reasoning-like process that operates at an unconscious level.

Phi movement An illusion of movement in which observers report the appearance of movement between two spatial positions, yet cannot perceive an object moving across the gap between the positions.

Retina Light-sensitive inner surface of the eye, onto which the visual image is projected; it contains photoreceptors that produce electrical signals when struck by light.

Keywords: (Check)

motion detection; adaptation; optic flow; figure–ground segregation; illusion
**Figure 2.** Explanation of the motion after-effect. Each motion ‘demon’ becomes active only when its preferred direction of movement is present in the image. One team of demons (‘L’) prefers leftward movement, and the other team (‘R’) prefers rightward movement. The two teams correspond to groups of motion-detecting neurons in the brain. The direction of perceived movement depends on the outcome of a tug-of-war competition between the two teams. In the presence of a stationary image, neither team is very active, so no motion is perceived (top). During exposure to rightward motion, the R team is more active than the L team and wins the competition, resulting in the perception of rightward motion (middle). Following adaptation (bottom), the R team takes a short time to recover from its previous activity, so the L team is more active in the presence of a stationary pattern, and wins the competition. As a result, illusory motion to the left is perceived.
**Figure 3.** Real movement versus apparent movement. Space is plotted horizontally and time is plotted vertically. In real movement (left) the disk changes position smoothly and continuously over time as it moves to the right. In apparent movement (right) the disk changes position just once over a relatively large distance, and is stationary at all other times. Both stimuli lead to the perception of motion.

**Figure 4.** Induced motion. The physical stimulus consists of a small stationary spot surrounded by a slowly moving frame (left). Perceptually (right), the frame appears to be stationary while the spot appears to move.
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Figures 1 and 2 captions, cf. text discussions: there is a lot of duplication of text here. Bearing in mind that they will be set close together in the finished volume, can any pruning of one or the other be carried out?