What You Don’t SEE Can Hurt You

Understanding the role of depth perception in slip, trip, and fall incidents

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A MAN WALKS DOWN A DIMLY lit hallway carrying a large, heavy box. The hallway is carpeted in fabric with a dark, complex pattern. The stairway at the end of the hall is covered in the same dark carpet as the hallway. When the man reaches the stairs, he steps down onto the first step but misjudges the distance. He loses his balance and falls down the stairs, severely injuring himself.

Similar incidents happen regularly. The man fell because he incorrectly judged the distance from the floor to the top of the first step. Like so many slip-and-fall accidents, this one was caused by an inaccurate perception of depth. The perception of depth is a complex process involving the unconscious interpretation of multiple visual cues and physiological responses. There is a significant margin for error in the way people perceive distance, and certain conditions can increase depth errors.

In this article, we give a brief overview of the mechanics behind the perception of depth and discuss the relationship between the perception of depth and slip-and-fall accidents. (Note that the literature cited here is largely contemporary; no attempt has been made to trace the literature through its complete classic or historic origins.)

The Physiology of Vision

When discussing sight, the analogy is inevitably made between the human eye and the camera. The eye and the camera are similar in many ways: Light enters a camera through an adjustable aperture very similar to the pupil; both control the amount of light that enters and keep it within a range that will provide the best results. In the camera, light is focused by a lens, or series of lenses, to provide a sharp image. The eye also uses a lens to focus light. The light focused by the lens strikes a layer of photosensitive cells on the back of the eye known as the retina.

Although the retina could be compared to a piece of photographic film, it is important to realize that the image the retina receives is not a photograph-like image of the world. The image on the retina is merely a crude display of light, dark, lines, and angles. This raw information is sent along the optic nerve to the brain and the visual cortex, where it is interpreted to produce the images that people see.

The Perception of Depth and Binocular Cues

The perception of simple, two-dimensional images is complex but understandable when the physiological aspects are made clear. Explaining the perception of depth in images is a little more difficult. In a way, our perception of depth is a paradox: We perceive in three dimensions, but the retina is like a movie screen and can only project in flat, two-dimensional images (Braunstein, 1976).

The primary visual cues are all binocular in nature, meaning that they require the use of both eyes to be effective. One of the most important binocular cues is known as *stereopsis.* In stereopsis, a phenomenon called *binocular disparity* occurs, which is a direct result of having two eyes separated horizontally on the head (DeAngelis, Ohzawa, & Freeman, 1991). When one observes an object, reflected light enters each eye and is projected onto the retina. The image that appears on the retina is affected by the distance of the object and the angle of the incoming light.

As Figure 1 shows, when the object is perceived by the right eye, the left side is farther away than the right side and thereby focused closer to the outside edge of the retina than to the right side. When the object is viewed by the left eye, the opposite it true. When compared side by side, two retinal images are mirror images of each other. The difference between the two images is the binocular disparity and must be processed through stereopsis and the visual cortex before it can provide any cues to depth.

With the assistance of binocular disparity, stereopsis is a powerful tool for determining depth (Patterson & Martin, 1992); it does, however, have its limitations (Bulthoff, Fable, & Wegmann, 1991). First and foremost, the distance information provided by stereopsis is not egocentric – that is, it provides distance between objects in the visual field but cannot calculate the distance between any object and the observer. Stereopsis is also inaccurate under certain conditions. At close distances, it tends to underestimate depth, and at far distances, it overestimates (Johnston, Cumming, & Parker, 1992). However, the greatest limitation of stereopsis is

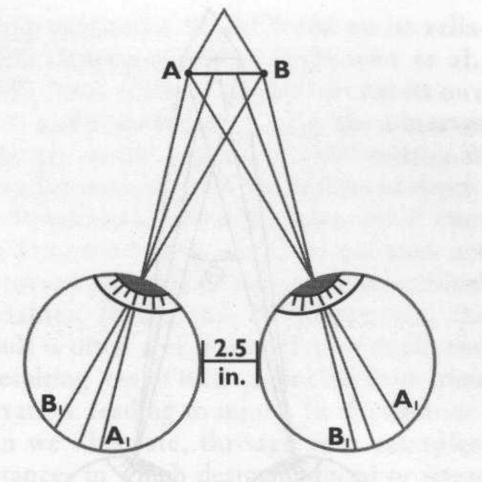


Figure 1. Binocular disparity.

its effective range. Stereopsis is effective only at short distances, about 200 meters or less (Ogle, 1973). This range limitation can be explained by the mechanism behind binocular disparity.

When an object is close to the observer, the angle of the light entering the eyes is acute, and the disparity between the two retinal images is great. As the distance between the object and the observer increases, the angle of the incoming light decreases, and the left and right retinal images become more similar, decreasing binocular disparity (see Figure 2 on page 18). If an object could be viewed at an infinitely far distance, the retinal images would appear identical. When the object being observed lies outside the range of stereopsis, there is not enough binocular disparity for stereopsis to be used, and the observer must rely on other monocular cues to determine depth.

Among the other binocular cues for depth is *convergence,* which is closely related to stereopsis. When observing an object at close distances, the eyes must turn inward to bring the object into focus (see Figure 3 on page 19). When the object is far away, the eyes assume a more neutral, straightforward position. The ocular muscles are responsible for controlling the angle of convergence; by doing so, they send feedback signals to the brain. By analyzing the ocular muscular feedback signals, the brain can approximate the angle of convergence.

Accommodation is a primary depth cue similar to convergence. In addition to changing the angle of convergence, the lenses of each eye can be manipulated by contracting

To determine depth at distances greater than the range of the binocular cues, monocular cues for depth must be used.

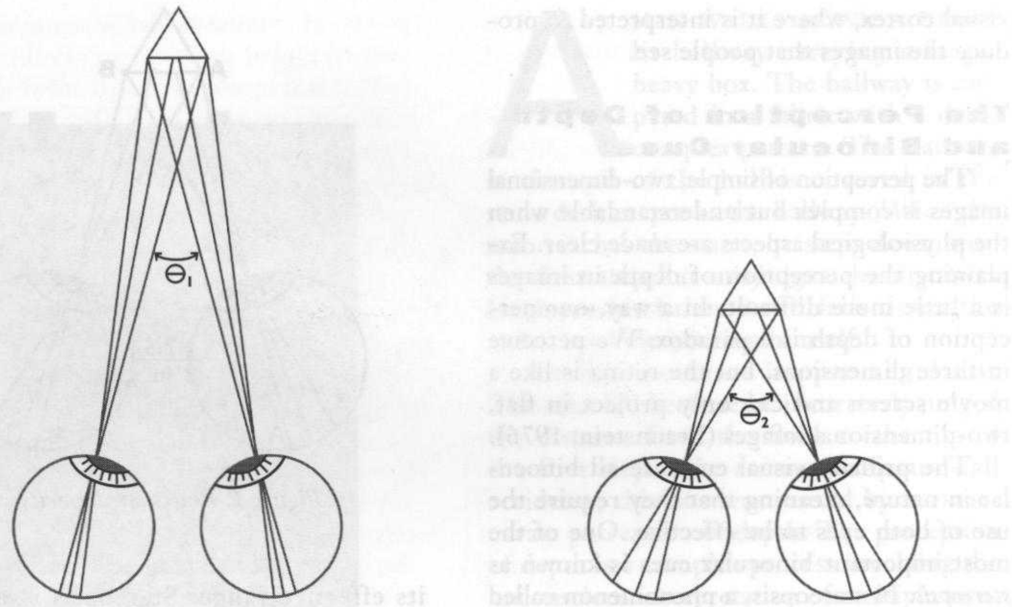


Figure 2. Decreasing binocular disparity.

When depth perception is adversely affected by poor lighting, lack of color or visual contrast, or deceptive visual patterns, depth cues send the brain erroneous information about one's immediate environment.

the muscles attached to each lens to help bring an image into focus. As in convergence, the feedback from these muscles is relayed to the brain, where it is interpreted to provide depth information.

Like stereopsis, convergence and accommodation are limited by their range: At distances greater than 200 meters, they lose most of their effectiveness (Braunstein, 1976). To determine depth at distances greater than the range of the binocular cues, monocular cues for depth must be used.

Monocular Depth Cues

Monocular depth cues are sometimes called *pictorial cues,* for reasons that become clear when one considers the structure of the visual system. In some ways, the retina is similar to a painting or a photograph. It is a two-dimensional image but succeeds at giving an impression of depth. Because all parts of the image are approximately the same distance from the observer, the binocular cues cannot be used, yet the impression of depth does exist.

Interposition is perhaps the most effective of the monocular depth cues. It occurs when an object appears to partially obscure another. Most visual illusions use interposition to trick the visual system into perceiving something that is not there. Fortunately, these illusions rarely occur, and interposition is usually able to provide an accurate, if sometimes vague, cue to depth.

Linear perspective is a very useful tool for estimating depth and is one of the easiest to describe. When two parallel lines are obscured in such a way that they project away from the observer, the two lines appear to move closer the farther they get from the observer (Braunstein, 1976).

Another effective pictorial depth cue is *familiar size.* If the actual size of an observed object is known, then the apparent size of the object on the retina can be used to approximate its distance (Haber, 1978). For example, if it is known that a C-5 military transport plane is approximately 250 feet long and a C-5 in flight appears one inch long, then its approximate distance is several miles from the observer.

Relative size is another size-dependent cue for depth and introduces the concept of retinal gradients (Braunstein, 1976). Retinal gradients occur when a repeating pattern of similar images are observed at increasing distances (Haber, 1978). One example of a relative size gradient is a full parking lot. All the cars in the lot are approximately the same size, but as the distance from the observer increases, the cars appear smaller. By comparing the apparent size of a distant object with the apparent size of a similar, much closer object, the relative distance to the distant object can be approximated.

Motion parallax is a powerful monocular depth cue that provides depth information by measuring the speed at which an image moves across the retina. As the eye moves from side to side, all the images in the retinal image also move to varying degrees (Braunstein, 1976). Typically, the closer an object is, the greater the amount it moves across the retina (Fraser, 1983).

By observing the amount that a given image moves across the retina, an approximation of its distance is possible.

Combination of Depth Cues

The visual system has myriad different depth cues at its disposal, but how does it combine them all to end up with one universal perception? When conflicting depth cues exist, there are three possible forms of cue interaction. When a strong cue, such as stereopsis, is challenged by a weaker cue, such as linear perspective, the stronger cue completely overrides the weaker cue in a process termed *vetoing*. In some circumstances, the interaction between two depth cues is recorded together to provide depth information. This is called *strong fusion* and can be seen when observing the rate of change of retinal disparity, the interaction of stereopsis and motion cues.

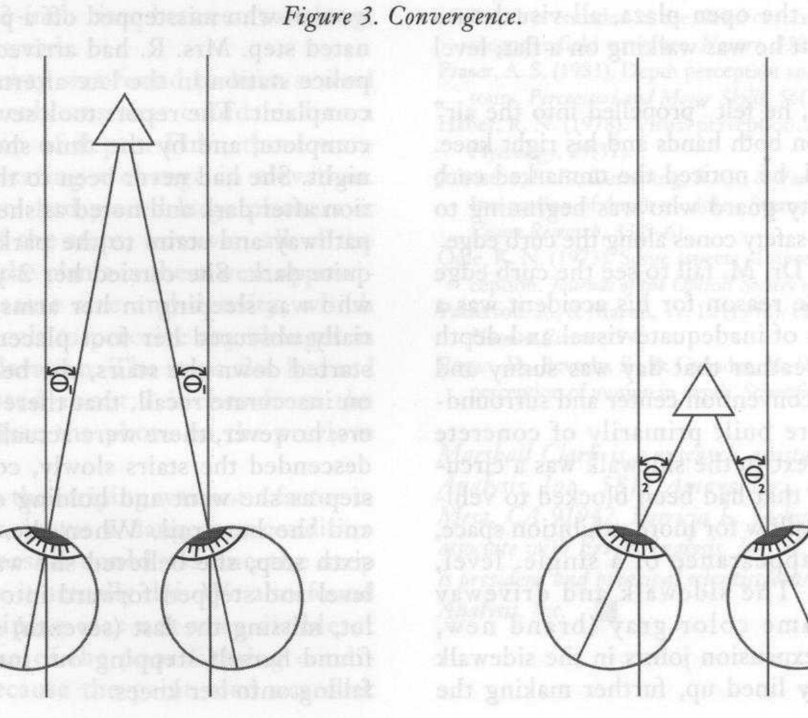
The last form of interaction is called *weighted linear combination* or, simply, weak fusion. In weak fusion, each depth cue is evaluated separately and then combined to form an overall impression of depth. Each cue is assigned a weight based on its reliability of measurement (Johnston et al., 1992). Each of these interactions has its own uses, and together they help the observer combine many sources of information to assemble one complete perception of depth.

Sometimes, however, false visual cues are presented or available visual cues are distorted by certain design or situational variables. In the case of pedestrians, the result is often a misperception of depth and a resulting loss of balance and fall from some elevation. leading to injury. In the next section we illustrate, through case examples, instances in which design-induced or situation-induced miscues resulted in false perceptions of depth and subsequent fall injury accidents.

Depth Perception in Accidents

How do the visual processes just described contribute to personal injury accidents? When depth perception is adversely affected by poor lighting, lack of color or visual contrast, or deceptive visual patterns, depth cues send the brain erroneous information about one's immediate environment, and a fall may result. In each of the following case histories – two missteps and one trip and fall – various inadequate lighting and visual cues created situations in

Figure 3. Convergence.



As he surveyed the open plaza, all visual cues indicated that he was walking on a flat, level surface.

Confusing walkway design.

Photo supplied by author

These different designs, combined with poor lighting, can visually confuse patrons, rather than guide them.

which the injured person's perception of depth was compromised.

The first case involves a 57-year-old man who misstepped and fell off a curb edge. Dr. M. and his wife were attending the grand opening of a new convention center at a city in Southern California. Dr. and Mrs. M. spent a couple of hours touring the inside of the convention center prior to the accident, then went outside onto the adjacent sidewalk. As Dr. M. walked across the sidewalk, he looked in his direction of travel. As he surveyed the open plaza, all visual cues indicated that he was walking on a flat, level surface.

Suddenly, he felt "propelled into the air" and landed on both hands and his right knee. After the fall, he noticed the unmarked curb and a security guard who was beginning to place orange safety cones along the curb edge.

Why did Dr. M. fail to see the curb edge and fall? The reason for his accident was a combination of inadequate visual and depth cues. The weather that day was sunny and bright. The convention center and surrounding area were built primarily of concrete and glass. Next to the sidewalk was a circular driveway that had been blocked to vehicle traffic to allow for more exhibition space, giving the appearance of a single, level, open plaza. The sidewalk and driveway were the same color gray (brand new, clean), and expansion joints in the sidewalk and driveway lined up, further making the area appear as one level surface. There were no visual cues, such as cars or planters, to assist in marking the change in elevation.

Convention center officials had also failed to paint and delineate curb edges prior to opening day. To compound the problem, Dr. M. was legally blind in one eye, thus compromising his binocular vision and depth perception. Despite this visual impairment, Dr. M. was the third of nine persons that day to seek first aid for similar missteps.

The second case involves a 37-year-old woman who misstepped off a poorly illuminated step. Mrs. R. had arrived at her local police station in the late afternoon to file a complaint. The report took several hours to complete, and by the time she left, it was night. She had never been to the police station after dark and noted as she left that the pathway and stairs to the parking lot were quite dark. She carried her 2-year-old son, who was sleeping in her arms, which partially obscured her foot placement. As she started down the stairs, she believed, based on inaccurate recall, that there were six risers; however, there were actually seven. She descended the stairs slowly, counting each step as she went and holding onto her son and the handrail. When she reached the sixth step, she believed she was at ground level and stepped forward into the parking lot, missing the last (seventh) step. Mrs. R found herself stepping out into space and falling onto her knees.

In Mrs. R's case, poor lighting and lack of visual cues created a situation in which she was unable to perceive a change of elevation and depth as she descended the stairs. As mentioned earlier, the pathway became darker as she approached the stairs. The nearest light source was a globe light approximately 12 feet away, and there was no direct illumination on or near the steps. Dense hedges also lined the sides of the stairs, casting dark shadows; only patches of light illuminated the steps. It is also important to note that the step edges were not marked and the handrails did not extend as they should beyond the last step – two important, but missing, visual depth cues.

The final case is a trip and fall involving a 53-year-old woman at a Southern California outdoor mall. Ms. H went to the mall with some friends for dinner one evening after work. She had never been to this new mall before and marveled at its unique architectural designs (for example, multitextured walkways and multiple stair designs). Ms. H and her friends had a cocktail on the patio area overlooking the ocean and watched the sunset before eating. When they got up to go into the restaurant, she noted that the area was somewhat darker than when they had arrived; however, no lights had been turned on. She walked toward the restaurant and suddenly found herself in midair and falling to her knees. The part of the walkway she thought was a ramp turned out to be a 4 1/2-inch riser between two long, landing-like treads.

The walkway was found to have several visual cue problems that could lead to a misperception of depth. First, there were no cues indicating a change in elevation. The designers had placed large planters at both ends of the steps; however, all of the planters and the plants in them were approximately the same size and density, which made it difficult to perceive any changes in height and elevation. The steps also had red stripes painted about 2 inches from the tread edges (see the photo on the previous page).

Although the striping was not a factor in this accident, it was a dangerous condition in that a person could assume the step ended before it actually did. We also found that the striping was not very visible at night because of the poor lighting conditions and because the paint used was dark and nonreflective. Finally, the area had several different walkway and stair designs and textures within proximity to each other. These different designs, combined with poor lighting, can visually confuse patrons, rather than guide them, giving them false perceptions and/or expectations based on prior or concurrent experience.

Conclusions

The process of visual depth perception is complex yet remarkable in its ability to function reliably most of the time based on only a few situational cues and people's past experiences. However, on occasion, certain design elements in the built environment combine to present either false or distorted visual depth cues, which can result in misperceptions, missteps, and resulting fall injury accidents.

The challenge, therefore, is for those responsible for designing, constructing, maintaining, and managing facilities to understand such phenomena and take appropriate steps to prevent trip and misstep accidents resulting from false or distorted visual depth cues. We hope that this article is a "step" in that direction.

References

Bulthoff, H., Fable, M., & Wegmann, M. (1991). Perceived depth scales with disparity gradient. *Perception, 20*(2).

Braunstein, M. L. (1976). *Depth perception through motion.* New York: Academic.

DeAngelis, G. C., Ohzawa, I., & Freeman, R. D. (1991). Depth is encoded in the visual cortex by a specialized receptive field structure. *Nature, 352*(6331).

Fraser, A. S. (1983). Depth perception and subjective contours. *Perceptual and Motor Skills, 56*(3).

Haber, R. N. (1978). Visual perception. *Annual Review of Psychology, 29*(31).

Johnston, E. B., Cumming, B. G., & Parker, A. J. (1992). Integration of depth modules: Stereopsis and texture. *Vision Research, 33*(5–6).

Ogle, K. N. (1973). Some aspects of stereopsis depth perception. *Journal of the Optical Society of America, 57*(9).

Patterson, R., & Martin, W. L. (1992). Human stereopsis. *Human Factors, 34.*

Regan, D., Beverly, K., & Cynader, M. (1979). The visual perception of motion in depth. *Scientific American, 24*(1).

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