Letter to the Editor

Commentary on Why Laryngeal Stroboscopy *Really* Works: Clarifying Misconceptions Surrounding Talbot's Law and the Persistence of Vision

Purpose: The purpose of this article is to clear up misconceptions that have propagated in the clinical voice literature that inappropriately cite Talbot's law (1834) and the theory of persistence of vision as the scientific principles that underlie laryngeal stroboscopy.
Method: After initial research into Talbot's (1834) original studies, it became clear that his experiments were not designed to explain why stroboscopy works. Subsequently, a comprehensive literature search was conducted for the purpose of investigating the general principles of stroboscopic imaging from primary sources.
Results: Talbot made no reference to stroboscopy in designing his experiments, and the notion of persistence of vision is not applicable to stroboscopic motion. Instead, two visual phenomena play critical roles: (a) the flicker-free perception of light and (b) the perception of apparent motion. In addition, the integration of stroboscopy with video-based technology in today's voice clinic requires additional complexities to include synchronization with camera frame rates.
Conclusions: References to Talbot's law and the persistence of vision are not relevant to the generation of stroboscopic images. The critical visual phenomena are the flicker-free perception of light intensity and the perception of apparent motion from sampled images. A complete understanding of how laryngeal stroboscopy works will aid in better interpreting clinical findings during voice assessment.

KEY WORDS: stroboscopy, endoscopy, vocal fold, voice, assessment

Laryngeal stroboscopy has become an essential component of the clinical voice evaluation because it enables the examiner to obtain a real-time visual estimate of vocal fold vibratory function. While doing research for a book chapter on the science of stroboscopy, we became aware of long-standing misconceptions in the clinical voice literature that primarily revolved around erroneous references to Talbot's law (1834) in attempting to explain why stroboscopy works. Given the apparent pervasiveness of this misapplied information, we felt compelled to provide this brief report in an attempt to clear up misconceptions in the literature regarding the scientific bases and origins of laryngeal stroboscopy. A more in-depth discussion of the science and technology that underlies laryngeal videostroboscopy is provided in the book chapter (Hillman & Mehta, 2010).

Brief History of Laryngeal Stroboscopy

Stroboscopy has its origins in the early 1800s, when it was discovered that the visual perception of motion could be elicited from a discrete set of pictures (Roget, 1825). During this time period, several household toys—for example, the phenakistiscope, zoetrope, daedaleum, and zoopraxiscope—were invented to exploit the stroboscopic phenomenon by making still pictures of objects appear to move by viewing the pictures through slits on a revolving disk (Wade, 2004). The periodic interruption of the viewer's line of sight produced a sequential sampling of the individual pictures in such rapid succession that motion was perceived.

Oertel (1895) published the earliest description of using stroboscopic principles to observe vocal fold vibrations (see Wendler, 1992; Zeitels, 1995). He constructed an instrument that rotated a disk with equally spaced holes to mechanically shutter a light source. The strobed light was reflected by a laryngeal mirror to illuminate the vocal folds and reflect a sequence of images that was perceived by the examiner as a slow-motion representation of the vocal fold vibratory pattern. This approach depended on subjects being able to adequately match their vocal pitches to the frequency at which the disk was rotating.

Modern clinical videostroboscopy systems automatically estimate the subject's vocal fundamental frequency from a neck sensor (usually a contact microphone or electroglottograph) as a basis for synchronizing the video capture rate to the flash rate of the strobe light (Rhino-Laryngeal Stroboscope 9100B/C; KayPENTAX, Lincoln Park, NJ) or shutter speed of the camera (StroboCAMII; JEDMED, St. Louis, MO) to record stroboscopic images of vocal fold vibration. The additional technological requirements for achieving synchronized video capture in modern laryngeal videostroboscopy systems are described in Hillman and Mehta (2010). In this report, we limit our discussion to clearing up basic misconceptions about which perceptual visual phenomena are associated with making laryngeal stroboscopy work.

Misconceptions

Throughout the 20th century and continuing to the present day, common misconceptions have been propagated in the clinical voice literature that involve the intertwining of Talbot's law with notions about the persistence of vision in attempting to explain how stroboscopy facilitates the examination of vocal fold vibration (cf. Bless, Hirano, & Feder, 1987; Colton, Casper, & Leonard, 2006; Kallen, 1932; Patel, Dailey, & Bless, 2008; von Leden, 1961; Wendler, 1992; Yanagisawa & Yanagisawa, 1993). For example, one source states that the stroboscopic effect arises when "fragmented sections become fused because of the phenomenon of Talbot's law, that is, the persistence of an image on the human retina for 0.2 seconds after exposure" (Colton et al., 2006, p. 241). This statement seems to indicate to the reader that a physiological limitation governs the human visual system's ability to perceive vocal fold tissue motion from strobed images and that Talbot's law determines that images must be displayed at least once every 0.2 s to achieve the desired effect.

Talbot's Law

In actuality, Talbot made no reference to the theory of persistence of vision or a temporal limitation on the visual system but, rather, conducted experiments related to the brightness of spinning disks. William Henry Fox Talbot is principally known for his seminal work in developing novel photographic chemical processes, particularly the calotype process that provided for the generation of multiple positive prints from a single negative print (Keller et al., 2005). Lesser known are Talbot's experiments on time-based measurements of light intensity that, although well-conceived in their own right, did not apply to the principles of stroboscopy. In one such experiment to estimate the intensity of light, Talbot rapidly rotated a white disk with a single black sector and noted that the perceived brightness of the rotating disk was "proportional to the angle of the [black] sector" (Talbot, 1834, p. 329). Any point on the disk was intermittently white or black at periodic intervals, and the perceived brightness of the disk was found to be linearly related to the duty cycle of white exposure. This relationship between exposure time and brightness became known as *Talbot's law.*

Persistence of Vision

The theory of *persistence of vision,* a phenomenon originally described by Aristotle, explains the simultaneous perception of objects from two images into one fused image (Wade, 2004). Such a fusion of two images was taken advantage of by the *thaumatrope,* a popular toy invented in the 1820s that involved rapidly spinning a disk around its diameter to create a single fused image from pictures on both sides of the disk. For laryngeal stroboscopy applications, however, the intent is not to fuse objects from more than one image onto one scene but, rather, to sequentially present short bursts of illumination to display a constant brightness in the image background and, further, to induce the visual perception of motion for objects in the foreground.

The ubiquity of the value of 0.2 s in the clinical voice literature likely lies in an article by Ervin S. Ferry titled "Persistence of Vision," which stated that the maximum "retinal impression" for the color white was 0.191 s (Ferry, 1892, p. 193). In his article, Ferry credited Joseph Plateau for determining this duration from experiments calculating the minimum speed at which a black-and-white disk must spin "to produce uniformity of tint" (Ferry, 1892, p. 193). Since the 19th century, much research has been done to better understand stroboscopic principles, and the idea that persistence of vision induces apparent motion in sequentially presented images has been shown to be a logical fallacy (Anderson & Anderson, 1993; Galifret, 2006). In fact, any persistence or overlap of an image onto a subsequent image would create an undesirable blurring artifact.

Visual Perceptions of Apparent Motion

Two visual perception phenomena play roles in laryngeal stroboscopy using direct observation: (a) the perception of a flicker-free uniformly illuminated background for presentation of the moving object and (b) the perception of apparent motion from sampled images when no real motion exists. Although the flicker phenomenon is unique to sampled images generated by strobing or shuttering of a light source, the perception of motion is a distinct phenomenon that is exploited not only by stroboscopic images but also by any video, movie, or motion picture constructed from a discrete set of images to create the illusion of apparent motion. Unfortunately, the distinction between these two visual phenomena is not made in the voice literature to accurately explain how laryngeal stroboscopy works, and the popular misconception has been to simply reference Talbot's law and the theory of persistence of vision without deeper understanding of stroboscopic principles.

As indicated earlier in this article, the first visual requirement of stroboscopy is eliminating the perception of flicker—that is, having perceived variation in object illumination or light intensity. Decades after the experiments by Talbot and Plateau, investigators used painted disks (Porter, 1898, 1902, 1912) and intermittently interrupted light sources (Hecht, Shlaer, & Verrijp, 1933a; Hecht & Verrijp, 1933b) to establish that, under usual circumstances, the rate of strobed illumination should be greater than about 50 Hz to be perceived as "flicker free." This frequency requirement is satisfied in laryngeal stroboscopy using direct observation, which employs strobe flash rates that are based on human fundamental frequencies well above 50 Hz.

The second visual requirement of stroboscopy is the perception of apparent motion—that is, the perception of a physically moving object when no real motion exists. Facilitating the perception of apparent motion relies on spatial and temporal requirements of the objects being sampled by the strobe light. Max Wertheimer (1912b) is credited with conducting seminal experiments that yielded temporal parameters necessary for the perception of apparent motion (see Galifret, 2006; Sekuler, 1996), with refinements made by later investigators on more complex stimuli (Burr, Ross, & Morrone, 1986). Wertheimer's experiments involved the successive presentation of two geometric figures separated by varying time intervals (Wertheimer, 1912/1916). Although the specific time intervals necessary for evoking apparent motion varied depending on experimental conditions, general numeric boundaries were reported by Wertheimer based on his empirical data. At presentation intervals shorter than 30 ms, the two figures were perceived to exist simultaneously (Wertheimer, 1912/1916). At intervals above 200 ms, the two figures were perceived to appear in succession. At intermediate interval durations, optimally around 60 ms, a single figure in motion was perceived. The 60-ms interval corresponded to a presentation frequency of about 17 images per second. These results defined the minimum frequency (17 Hz) at which a sequence of strobed images would be perceived to exhibit apparent, continuous motion.

Stroboscopic Examination of Vocal Fold Vibration

Once the requirements of the visual system are met to induce apparent motion, the task turns to selecting the images that will be displayed to create this motion. Stroboscopic sampling can be used to create the optical illusion of slowing down and better revealing an underlying pattern of rapid motion, such as the vocal fold vibratory pattern. Stroboscopy can enable two views of periodic motion—it can appear to freeze the motion at a selected phase in the repeating pattern, or it can create an apparent slow-motion view of the repeating pattern (i.e., a display of the entire period or cycle).

Laryngeal stroboscopy creates an apparent slow-motion view of periodic vocal fold vibrations by effectively sampling successive phases of the movement across successive vocal fold cycles. The method is analogous to the auditory perception of a *beat frequency* that occurs when two periodic stimuli close in fundamental frequency are presented to a listener. The beat frequency is equal to the absolute difference between the frequencies of the two tones. By analogy, the number of slow-motion cycles per second produced by the stroboscopic effect is equal to the difference (the *visual beat frequency*) between the fundamental frequency of the real vocal fold motion and the strobe frequency. The strobe frequency must be less than the fundamental frequency in order to sample successive phases of the cycle. If the strobe frequency were greater than the vocal fold's fundamental frequency, the vocal fold cycle would appear to be moving in reverse—an effect referred to as *time aliasing*.

Typically, an observer desires the apparent motion of the vocal folds to be presented at a beat frequency between about one-half cycle per second and two cycles per second; otherwise, the motion would be too slow for practical assessment or too fast for the eye to follow (and thus defeating the purpose of using stroboscopy). As expected, the desired beat frequency or strobe effect can be achieved through modification of either the strobe frequency or the fundamental frequency of vocal fold vibration. For example, to produce the perception that vocal folds vibrating at 100 Hz are slowed down to 2 cycles per second (beat frequency of 2 Hz), the strobe frequency must be set to 98 Hz. Alternatively, if the strobe frequency were fixed at 100 Hz, an individual must phonate with a fundamental frequency of 102 Hz to achieve the same strobe effect of 2 cycles per second. In either case, the strobe frequencies satisfy the visual–perceptual conditions necessary for flicker-free illumination (>50 Hz) and the perception of continuous, apparent motion (>17 Hz).

Further complexities must be taken into account when integrating video-based technologies with stroboscopy, as it is typically done in laryngeal videostroboscopy systems that are currently in clinical use (JEDMED, 2009; KayPENTAX, 2008). In clinical practice, the flicker-free requirement is relaxed, as flicker is often perceived in clinical videostroboscopy systems due to slight deviations in the intensity of the strobe light from image to image. This article focused on clearing up misconceptions related to stroboscopic principles, and we present a detailed discussion addressing interactions of the strobe rate with video camera rates in our book chapter (see Hillman & Mehta, 2010).

Conclusion

In summary, through this brief report, we sought to clarify misconceptions that have propagated in the literature regarding the scientific principles of laryngeal stroboscopy. It was shown that references to Talbot's law and the persistence of vision are not relevant to the generation of stroboscopic images. Instead, the critical visual phenomena that apply to direct stroboscopic observation of vocal fold vibration are the flicker-free perception of light and the perception of apparent motion from sampled images.

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Acknowledgments

This work was supported by National Institute on Deafness and Other Communication Disorders (NIDCD) Grants T32 DC00038 and R01 DC007640 and by the Institute of Laryngology and Voice Restoration. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the NIDCD.

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Received November 25, 2009

Accepted March 26, 2010

DOI: 10.1044/1092-4388(2010/09-0241)

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