Carl Pulfrich and the role of instruments to identify and demonstrate the *Stereo-Effekt*

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The present results were presented in part at the 66th Annual Meeting of the American Academy of Neurology, Philadelphia, PA on April 28, 2014.

ABSTRACT

Background. The *Stereo-Effekt*, described by German physicist Carl Pulfrich in 1922, is an illusory binocular perceptual disturbance of moving objects that is most commonly associated with unilateral or asymmetric optic neuropathies.

Methods. We translated and reviewed Pulfrich's description of the phenomenon, surveyed the stereoscopic equipment Pulfrich developed that brought the *Stereo-Effekt* to attention, and analyzed the models that Pulfrich subsequently built to demonstrate this phenomenon to audiences.

Results. In 1899, Pulfrich developed an optical device for measuring the position of objects using stereophotographs, thereby transforming the stereoscope into a measuring instrument (*Stereokomparator*). Around 1919, German astronomer Max Wolf reported that a peculiar stereo phenomenon sometimes interfered with taking precise measurements of astronomical objects using the *Stereokomparator*. Pulfrich and his colleagues determined that this *Stereo-Effekt* was due to a difference in brightness between the photographic plates. Despite Pulfrich's inability to observe the phenomenon himself due to acquired monocular blindness, he and his colleagues elaborated a reasonable psychophysiological model and developed demonstration models that served both to exhibit the phenomenon to others and to further explore its underlying psychophysics.

Conclusion. Pulfrich described the *Stereo-Effekt* after technical difficulties were observed by users of an optical apparatus he had devised. Pulfrich's demonstration devices helped prove that the observed phenomenon was not due to a technical fault of the original apparatus, allowed the phenomenon to be exhibited to audiences, enabled further scientific study of the phenomenon, and led to his discovery of an unrecognized clinical disorder (i.e., spontaneous *Stereo-Effekt* in patients with anterior visual pathway disorders).

KEYWORDS
Clinical neurology, optic neuritis, history of neurology, optic nerve, Pulfrich effect, visual processing

Introduction

The Pulfrich effect is an illusory binocular perceptual disturbance in which an object moving horizontally across an observer's field of vision is perceived as travelling closer or farther with respect to the actual distance from the observer as a result of a difference in perceptual latency between the two eyes.[1] The effect can be induced (e.g. by placing a neutral density filter [NDF] over one eye) or it can occur spontaneously with prechiasmatic visual pathway lesions. Either situation produces a unilateral delay in signal processing, so that an object moving across the field of vision is perceived by the affected eye to be in a lagging position relative to the position perceived by the unaffected (or less affected) eye. The resulting difference in retinal image location for the two eyes (binocular disparity) alters the perceived *distance* of

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Received: 27 November 2014 / Accepted: 19 December 2014

Figure 1. German physicist Carl Pulfrich (1858-1927) in 1889. Public domain. Courtesy of Wikimedia Commons

the moving object, and in so doing it produces a distortion in depth perception; this distortion applies only for objects moving relative to the observer.

Patients with a spontaneous (pathologic) Pulfrich phenomenon commonly report errors in visual localization of moving objects, or of stationary or moving objects when the patients themselves are moving. Thus, for example, they may report that oncoming traffic or parked cars appear to curve in toward them when they are driving, that they have a tendency to bump into people or stationary objects while walking, or that they have difficulty hitting a rapidly moving target while playing sports (e.g., squash, tennis, baseball).[2-12] Clinically, the effect has been noted most commonly as a manifestation of unilateral or asymmetric optic neuropathies, and it may be a presenting manifestation of multiple sclerosis, but it can also occur in unilateral or asymmetric ocular disorders (e.g., cataracts, central serous retinopathy, macular hole, etc.).[6,8-12] It is typically assessed in clinical practice using a pendulum, and a suspended bob moving across a background of black felt has proven to be a reliable way of observing the phenomenon in patients, although results using a bedside “swinging pen test” have been reported to correlate well with those from mechanical pendulum tests in patients with optic neuritis.[13-14]

In the 1970s, assessment of the presence of a spontaneous Pulfrich effect was used as a complementary method for diagnosing optic nerve disorders, and particularly retrobulbar optic neuritis in patients with possible multiple sclerosis.[15-21] It proved to be of comparable utility to visual evoked potential studies for this purpose, and was simpler, quicker, and less expensive, but it required that test subjects have intact stereopsis, and abnormal results could not distinguish between unilateral and asymmetric bilateral dysfunction.[19] Its use as a diagnostic test was further limited by the absence of a standardized testing procedure, and by the subsequent development of objective technologies such as MRI and optical coherence tomography of the retinal nerve fiber layer. It is nevertheless important to recognize this phenomenon in affected patients because it produces symptoms which patients (and clinicians) often find puzzling; , and because untreated symptoms are often disturbing to patients, may interfere with activities, and may in some circumstances be dangerous; and because it is easily treated.[6-8,21,22]

German physicist Carl Pulfrich (1858-1927) (Figure 1) first described this *Stereo-Effekt* in 1922 in a lengthy and wide-ranging five-part paper.[1] Pulfrich not only demonstrated an inducible *Stereo-Effekt* by placing a smoked glass (i.e. an approximation of an NDF) over one eye, he also recognized that visual pathway disorders can produce a pathological *Stereo-Effekt*. In 1925, only three years after Pulfrich’s report, British consulting ophthalmic surgeon Harold Barr Grimsdale (1866-1942) demonstrated a pathological *Stereo-Effekt* in a man with unilateral retrobulbar optic neuritis and proposed that such perceptual disorders could be treated with an NDF over the *unaffected* eye.[6] Later authors demonstrated that an NDF placed in front of the good eye is in fact effective for treating patients with perceptual disorders resulting from the Pulfrich effect.[22,23]

The purpose of this article is to review Pulfrich’s development and use of instruments to analyze and demonstrate this visuo-perceptual phenomenon.

Methods

We translated and reviewed Pulfrich's description of the phenomenon,[1] surveyed the stereoscopic equipment Pulfrich developed that brought this phenomenon to attention, and analyzed the models that Pulfrich subsequently developed to demonstrate the phenomenon to audiences. We searched for Pulfrich's original instruments in Germany in such institutions as the ZEISS Archiv in Oberkochen, the Deutsches Museum in Munich, and the Optisches Museum in Jena. We also sought biographical information on Pulfrich and his colleagues in published biographies and obituaries, and in unpublished material in the ZEISS Archiv.

Results

Pulfrich was born in Burscheid, near Düsseldorf, Germany; he was the eldest son of a teacher. He attended the *Gymnasium* in Mühlheim by the river Ruhr, and then studied physics, mathematics, and mineralogy at the University of Bonn, where he received his PhD in optics in 1881.[24,25] Subsequently, he completed his military service, and then worked as an instructor at the Physics Institute at the University of Bonn.[24,25] In 1890 he was recruited to lead the new Section for Optical Measurement Instruments at the Optical Factory of Carl Zeiss Works (*Zeiß Werkstätten*) in Jena, Germany, where he ultimately became the preeminent authority on stereoscopic instruments.[1,24-29] Pulfrich's scientific contributions encompass more than 100 publications, concerning three major research areas: refractometry (1885-1899), developing instruments for measuring refractive indices to assess composition or purity of substances; stereoscopy and particularly the subfield of stereo-photogrammetry (1899-1923), developing instruments for estimating the three-dimensional coordinates of objects determined by measurements made in photographic images taken from different positions; and photometry (1920-1927), developing an instrument to measure the intensity of the light produced by an unknown source in terms of a standard source. Because of these scientific contributions, Pulfrich was recognized with various professional honors. In 1917, he was awarded the title of Professor by the Prussian government; in 1923, for founding the field of stereo-photogrammetry (research that led to his discovery of the *Stereo-Effekt*), he received an honorary doctor of engineering degree from the Technical University of Munich; and in 1926, near the end of his scientific career, he was elected to be a member of the Royal Leopoldine Academy of Natural Scientists in Halle.[25]

In 1899, Pulfrich transformed the stereoscope into a measuring instrument by inventing and developing the stereo-comparator (*Stereokomparator*), an optical device designed to accurately compare stereoscopic photographs for photogrammetry, i.e., measuring the position and shape of objects from paired photographs of the same subject taken from different horizontal positions (Figure 2).[30-33] The stereo-comparator had two key parts: a framework to carry the stereo photographic plates, and a binocular microscope for viewing them. Pulfrich presented the instrument on September 23, 1901, at the *Gesellschaft Deutscher Naturforscher und Ärzte* (Society of German Scientists and Physicians) in Hamburg.[30] Pulfrich's first experimental stereo-comparator is now in the collections of the Deutsche Museum in Munich, and images are also available in the ZEISS Archiv.

Around 1907, Lieutenant Eduard von Orel (1877-1941) of the Austrian Military Geographical Institute of Vienna developed the first prototype stereoautograph able to mechanically trace elevation contours directly without tedious and time-consuming computational interpolation methods.[28, 34-36] The first prototype used the Pulfrich

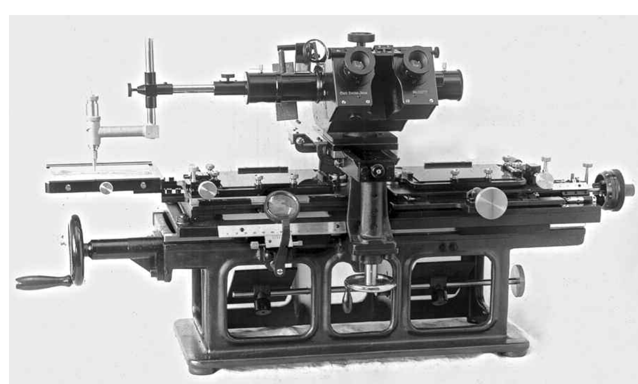

Figure 2. Photograph of Pulfrich's stereo-comparator (*Stereokomparator*, 1901), an optical device designed to accurately compare stereoscopic photographs. Frontal view of the apparatus. Courtesy of ZEISS Archiv.

stereo-comparator in combination with a geometrical linkage system and a plotting device.[36] Zeiss began manufacturing an improved version of this instrument in 1909 (Figure 3), and it proved to be the first commercially successful instrument for automatic plotting of contours. These measuring instruments found widespread application in surveying, but were also applied in astronomy and other fields.

One of the pioneers in the use of Pulfrich's stereo-comparator was German astronomer Maximillian (Max) Wolf (1863-1932) (Figure 4), who was the director of the States Astrophysical Observatory at Königstuhl and professor of astrophysics and geophysics, and ultimately chair of astronomy at the University of Heidelberg.[37-40] Wolf had received his PhD from the University of Heidelberg in 1888, working under German mathematician Leo Königsberger (1837-1921). In 1893, Wolf was appointed to supervise construction of the astrophysical portion of the historic Landessternwarte Heidelberg-Königstuhl astronomical observatory, which was built from 1895 to 1900 on the summit of the Königstuhl (or "King's seat"), a 567-meter-high hill outside of the city of Heidelberg.[39] In his work there, Wolf became a pioneer in the use of wide-field photography, and he used this particularly in the search for asteroids by noting a shift in position of objects across sequential photographs, a lengthy, tedious, and error-prone process as it was originally implemented.[37,39]

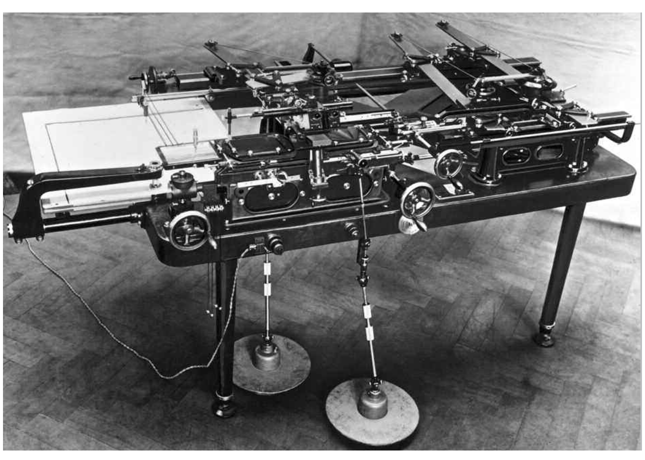

Figure 3. The Zeiss stereo-autograph (1909), which was used to mechanically trace elevation contours directly without the tedious and time-consuming computational interpolation methods needed with the stereo-comparator. The first prototype of this instrument was developed around 1907 by Lieutenant Eduard von Orel (1877-1941) of the Austrian Military Geographical Institute of Vienna. Zeiss began manufacturing an improved version of this instrument in 1909, and it proved to be the first commercially successful instrument for automatic plotting of contours. The device combined the Pulfrich stereo-comparator (front left on table) with a geometrical linkage system and a plotting device. Courtesy of ZEISS Archiv.

Wolf's initial test of the stereo-comparator in 1901 used two photographs of Saturn, taken on consecutive days in 1899; when viewed in Pulfrich's device, "the planet and two of its satellites appeared suspended in space, far in front of the background formed by the stars".[38(p250-1)] Wolf then asked Pulfrich to examine serial plates on which several asteroids had been recognized after a careful search. Using the stereo-comparator, Pulfrich "recognized the asteroids suspended in space after a few minutes' comparison, although quite unaccustomed to examining astronomical photographs, and, in addition, pointed out another asteroid" that Wolf had overlooked.[38(p251)] In addition, during the initial test of the stereo-comparator in 1901, ten variable stars in the Orion nebula were found.[33] Wolf and Pulfrich subsequently engaged in a steady exchange of letters concerning Wolf's applications of the stereo-comparator to astronomy, including visualizing Saturn and its moons (1901) and the tails of comets (1902), and the discoveries of various asteroids (beginning in 1901), variable stars (1901-1903), and supernovae (1909-1926).[33,38,41,42]

In 1919, Wolf reported that a peculiar stereo effect sometimes interfered with obtaining precise measurements of astronomical objects using the stereo-comparator.[43] When the stereoscopic plates of a star were adjusted in the stereo-comparator to produce an image which appeared to coincide in space with the stereoscopic image of the distance indicator on the instrument, Wolf found with some sets of plates that the image of the star seemed to move either in front of or behind its original position if the plates were quickly moved laterally.[45] As Pulfrich noted,

> I had not heard of these irregularities until Professor Max Wolf from the Königstuhl in Heidelberg had published his work on the celestial path of 1053 stars[43] that had been measured with the stereo-comparator. In his paper Professor Wolf mentions a peculiar stereo effect as an occasional distraction, which he noted while scanning photographic plate pairs. It consisted of a noticeable forward or backward separation of a star's image from the reference marker during fast movement of the photographic plates.[1]

Pulfrich subsequently learned that others had noted similar problems with the stereoautograph during the early years of that instrument's use in landscape surveying:

> After having carefully adjusted the marker to a specific point in the landscape it could occasionally be seen to follow a circular path around the object point during rapid back-and-forth movement of the photographic plates. One usually resorted to the self-assuring explanation that the mechanical link between the plates had accidentally loosened by a small amount.[1]

Pulfrich and his colleagues initially suspected that the disturbance resulted from a change in separation between the stereoscopic plates (e.g., a loose connection in the plate-bindings), but subsequent investigation showed that the apparent spatial displacement was caused by a difference in overall brightness between the two plates. Two of Pulfrich's colleagues at the Zeiss Company, engineer Joh (Johann) Franke and instructor (*Studienassesor*) Ferdinand Fertsch (1889-1981), "determined that the observed aberrations were not related to a separation of the plates during joint sideways motion."[1] If such a separation had been present, it would have indicated a technical fault of the equipment that could potentially have damaged the reputation of the company. Instead, they determined that "the sole reason [for the phenomenon] was a *difference in the brightness between the left and the right plate*" [original emphasis], because "photographic plate pairs which were originally free of the aberration could display it when their illumination became unequal" and "plates which demonstrated the phenomenon no longer yielded it when their illumination was balanced." Consequently, before initiating measurements with the stereoautograph, operators were advised to assess for equivalent illumination of the plates by placing a marker on a point in the landscape and then moving the plate pair back and forth. Apparent rotary movements indicated unequal illumination of the plates, which could then be corrected or compensated:

> [We] no longer view the "circling marker point" as a discomforting aberration, but rather as an indicator for the presence of a brightness difference and a stimulus to either abolish it, for instance by dimming the brighter lamp with one or several sheets of tracing paper, or to avoid its adverse effects on the measurement by slowing the movement of the plate pair.[1]

By testing perception with plates of unequal illumination, Pulfrich and colleagues demonstrated that the direction of rotation depended on which plate was brighter:

> [The] marker circles around the object point in a clockwise movement when viewed from above, similar to the crank of a coffee mill, *when the right eye receives the brighter image. The movement becomes counterclockwise when the left eye sees the brighter image* [original emphasis].[1]

Pulfrich himself was unable to view the phenomenon because he was by then blind in his left eye:

Figure 4. German astronomer Max Wolf (1863-1932). Wolf pioneered the use of the Pulfrich stereo-comparator in astronomy. Later he noted technical difficulties that Pulfrich and colleagues ultimately identified as resulting from unequal illumination of the stereo photographs being compared. Work on this technical problem led Pulfrich and colleagues to a practical technical solution, but also led them to recognize a general perceptual illusion and to propose a pathophysiological mechanism for this phenomenon. Public domain. From Hector MacPherson.[38]

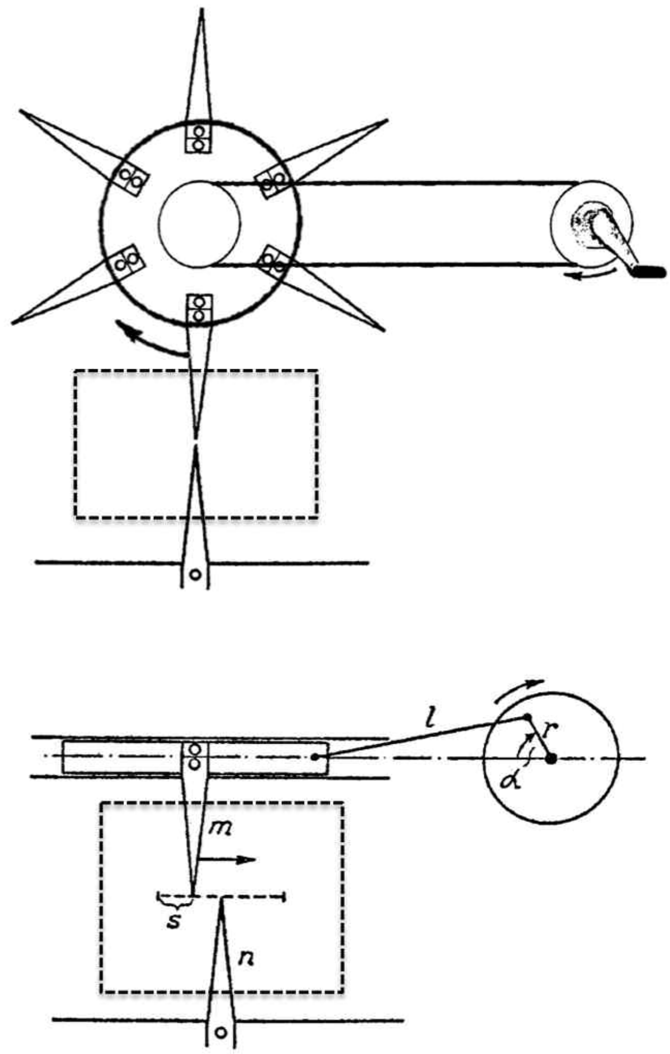

Figure 5. Diagrams showing Pulfrich's two demonstration devices to show the stereo-phenomenon to audiences. (Pulfrich, 1922). Pulfrich's demonstration models used unidirectional rotary motion and bidirectional harmonic motion; neither was pendular, although in later clinical use the Pulfrich phenomenon has been assessed with pendular motion. The top figure was drawn by JML from information in Pulfrich's original article, whereas the bottom figure is from Pulfrich's article.[1] Public domain.

> I have never been able to observe said disturbances myself since I have been blind in my left eye…following a severe ocular injury in my youth.…Nonetheless, I felt challenged to pursue the phenomenon further and to attempt to understand the underlying principles.[1]

Demonstration of the Stereo Effect

Despite Pulfrich's personal inability to observe the phenomenon, he developed a series of demonstration models that served both to present the phenomenon to others and to further explore the psychophysics of that phenomenon. Observers were instructed to place a smoked glass over one eye to reproduce the type of asymmetry in brightness for the two eyes that had initially brought the phenomenon to attention with the stereocomparator.

> The phenomenon…can be easily demonstrated to a larger audience, with the only requirement being that each observer has a piece of smoked glass, or

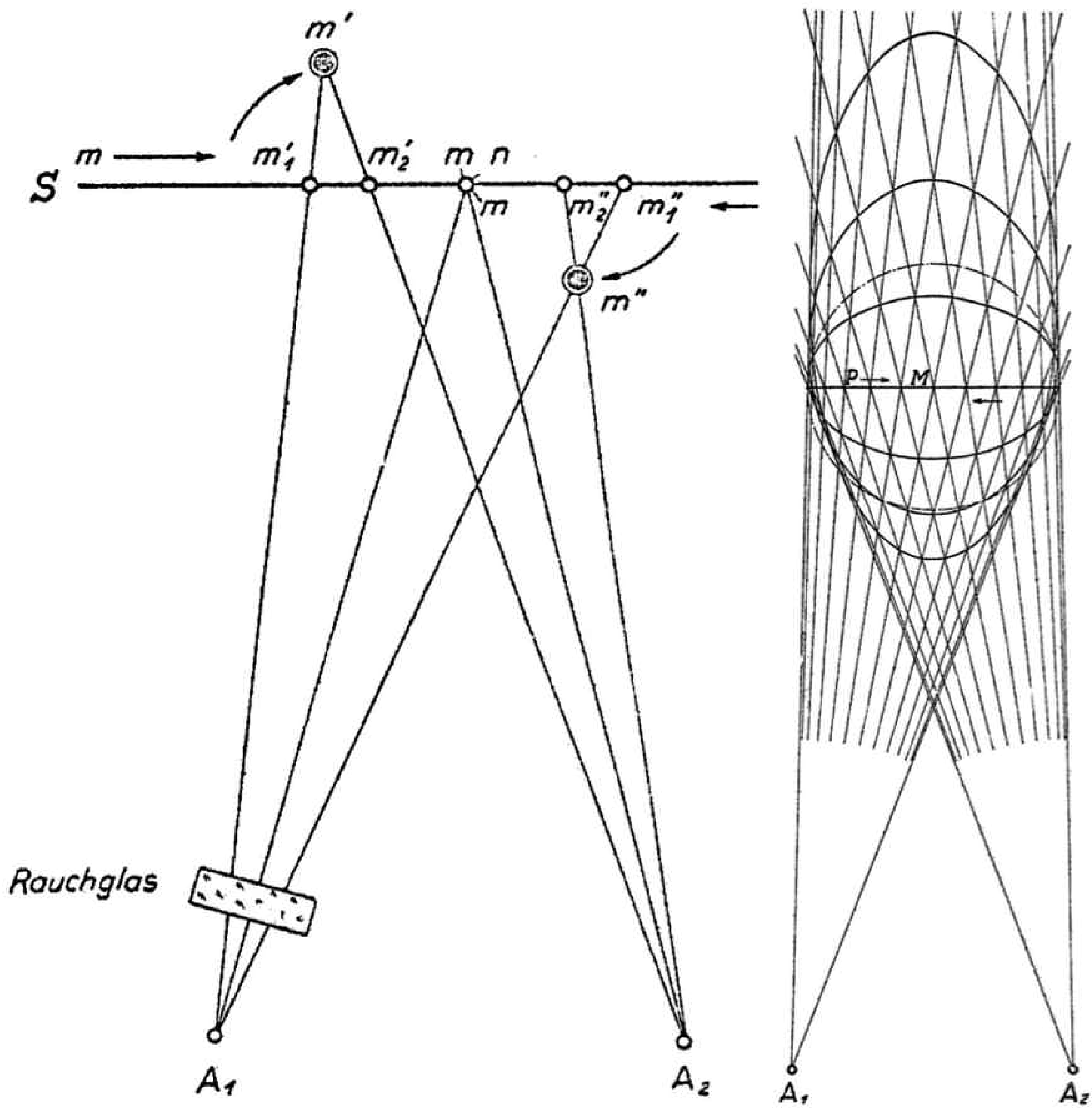

Figure 6. Pulfrich's diagrams of the mechanism of the stereo-phenomenon (left), and the perceived trajectories of an object moving back and forth across the field of vision in linear harmonic motion at different velocities (right).1 According to Pulfrich and colleagues, placing a neutral-density filter over the left eye (*Rauchglas* = smoked glass) produces a perceptual latency for that eye. Consequently, an object moving from the right (the side opposite from the neutral-density filter) is perceived with a lag that produces a crossed binocular disparity, so it is perceived as closer than its true position. Similarly an object moving from the left (the same side as a neutral-density filter) is perceived with a lag that produces an uncrossed binocular disparity, so it is perceived as farther away than its true position. For an object moving in linear harmonic motion, the perceived trajectories are closed curves that resemble ellipses for slower target speeds, with lessening eccentricity (greater excursion in the transverse plane) as target speed increases. At even higher speeds, Pulfrich suggested the perceived trajectory becomes asymmetric.

> another device which enables dimming of visual input to one or the other eye. Individuals who have no stereoscopic vision for whatever reason will naturally have to forgo the experience of the stereo-effect.…Generally observers will not notice a spontaneous stereo-effect. However, as soon as the smoked glass is placed in front of one or the other eye, the effect manifests in the most obvious way such that the leftward moving marker passes behind the fixed marker when the glass is placed in front of the left eye. During rightward movement, the marker passes in the front. The effect intensifies with increasing velocity. When movement is suddenly stopped the markers again appear at the same distance.[1]

Pulfrich's demonstration models used different types of motion for the target (Figure 5). With the first model, using rotary motion, six rotating spikes appeared to pass either in front of or behind a stationary marker, depending on the direction of rotation. The second model, featuring a back-and-forth oscillation along a line, was driven by a hand-cranked wheel turning at a uniform angular speed; this latter mechanism produced linear harmonic motion of the target.

Although a pendulum is now most often used to demonstrate the Pulfrich effect, Pulfrich himself did not propose this approach. Nevertheless, he was clearly aware that the stereo effect could be appreciated using a pendulum, because he mentioned his surprise that the phenomenon had not been recognized earlier, given that every clockmaker's shop offered the possibility of discovering it by virtue of the numerous swinging pendulums on display. Pulfrich did not recommend a pendulum for demonstrations or testing because, without using a bifilar suspension or swinging the weight on a rigid rod, a handheld bob on a string was liable to swing in a rotary path, which would confound testing:

> Indoors and during the day, I recommend the following arrangement: attach a pencil with wax on a window that is oriented toward the bright sky and slide a second, also vertically oriented pencil beneath it back and forth. Contact of the pencil with the windowpane is recommended as a free hand will too easily follow an arced path. In the evenings one can use an illuminated sheet of white paper on a table as the background for the two pencils. Considering how easily the phenomenon of the circling markers can be elicited it is surprising that it has not been observed before, especially since every clockmaker's shop offers the opportunity. This situation illustrates modern man's diminished ability of pure observation that should be free from the influences of thought [cognitive bias] and experience.

In addition to the use of a smoked glass, Pulfrich noted several other ways of inducing the phenomenon by "dimming one eye", (e.g., squinting with one eye, or placing in front of one eye either a pinhole or a colored filter). However, Pulfrich found that some subjects could observe the effect *spontaneously* because of an existing visual defect in one eye. He suggested rather casually that such individuals would be of clinical interest as a means of identifying patients with unilateral or asymmetric dysfunction of the anterior visual pathways:

> As it turns out there are individuals who do perceive a circular motion without added devices, i.e., clockwise or counterclockwise, depending on whether the left or the right eye responds faster. In such patients, who are of special interest to ophthalmologists, a more or less pronounced difference between the eyes…could be demonstrated every time. [1]

Discussion

Pulfrich discovered the *Stereo-Effekt,* later called the "Pulfrich effect," after technical difficulties became apparent among users of a specific optical apparatus, the *Stereo-komparator*.[1] Pulfrich himself was unable to view the phenomenon because he lacked stereovision due to traumatic blindness in his left eye, but he was nevertheless able to elaborate a plausible psychophysiological model and build instruments to demonstrate the *Stereo-Effekt*. Pulfrich's demonstration devices helped prove that the observed phenomenon was not due to a technical fault of the original scientific apparatus, allowed the phenomenon to be exhibited to audiences by projection, enabled further scientific study of the phenomenon, and led to his discovery of an unrecognized clinical disorder among individuals who had a spontaneous *Stereo-Effekt* due to dysfunction of the anterior visual pathways.[1]

Pulfrich's demonstration devices used two different types of target movement to demonstrate the effect with a smoked glass placed over one eye. The first demonstration apparatus used rotary motion, causing the targets on the rotated wheel to appear to move toward or away from the observer depending on the direction of rotation. The second demonstration apparatus used simple one-dimensional harmonic motion, generating an observed elliptical path. In later studies of the Pulfrich phenomenon, American psychologist Alfred Lit (1914-2000)[44-46] and subsequent investigators[13,47] used a variant of Pulfrich's second demonstration device, i.e., a "Scotch yoke" (or slotted-link mechanism) that converts rotational motion (from a pin on a spinning wheel) into linear motion by direct coupling to a sliding yoke with a slot that engages the pin on the wheel.

Pulfrich dismissed the use of a pendulum to elicit the effect because it was difficult to keep the pendulum swinging in a single plane. The varying trajectory would confound assessment of the *Stereo-Effekt*. Some later investigators, while trying to use the Pulfrich effect to develop a diagnostic test for optic nerve disorders, found that use of pendulums gave inconsistent results and they then employed more sophisticated techniques instead.[18] Nevertheless, a pendulum was most often used for clinical evaluation or testing, either at the bedside or in an office setting with a bifilar suspension (i.e., using two strings to suspend the bob in a "V" configuration to constrain the swing of the bob to a single vertical plane).[3,48] Some investigators misleadingly referred to other non-pendulum devices that generate simple harmonic motion as "pendulums," including the Scotch-yoke mechanism employed in Pulfrich's second demonstration device.[13,47]

A simple pendulum confined to one vertical plane exhibits simple harmonic motion under the conditions of no damping and small amplitude. With the assumption of a small angular displacement (amplitude), the frequency and period of the pendulum are independent of the initial angular displacement or amplitude. The small angle approximation is valid for initial angular displacements of about 20° or less. However, for larger amplitudes, like those commonly used in clinical applications, the motion of the pendulum is more complex mathematically and, in contrast to that elicited by Pullfrich's second demonstration apparatus, it includes a significant vertical component. As a result, there are both horizontal and vertical binocular disparities.

Binocular disparity refers to the difference in image location of an object seen by the left and right eyes, typically resulting from the horizontal separation of the eyes. The brain uses binocular disparity to extract depth information from the two-dimensional retinal images. English scientist Sir Charles Wheatstone, FRS, (1802-1875) had shown by 1838 that horizontal binocular disparities are sufficient for the perception of stereoscopic depth.[49] Indeed, perceived depth increases monotonically with horizontal disparity from threshold to the limit of binocular fusion.[50] Objects with uncrossed horizontal disparities are seen on the far side of the fixation plane, while objects with crossed horizontal disparities are seen on the near side.

Pulfrich credited his junior colleague Ferdinand Fertsch with the most widely accepted explanation for the phenomenon as resulting from differences in perceptual latency between the two eyes[1], an interpretation which relies on the now-accepted idea that inequalities in binocular illumination result in unequal visual-perceptual latencies.[18,44,47,51-53] With a moving target, the delay in perceptual latency creates a horizontal binocular disparity that is interpreted as a change in distance of the object.

Placing a smoked glass (*Rauchglas*) or NDF over the left eye produces a perceptual latency for that eye, just as would a left-sided prechiasmatic abnormality (e.g. optic neuritis) (Figure 6). Consequently, an object moving from the right is perceived with a lag in the left eye that produces a crossed binocular disparity, so it is perceived as closer than its true position. Similarly an object moving from the left is perceived with a lag in the left eye that produces an uncrossed binocular disparity, so it is perceived as farther away than its true position. For an object moving in linear harmonic motion, the perceived trajectories are closed curves that resemble ellipses for slower target speeds, with lessening eccentricity (greater excursion in the transverse plane) as target speed increases. At even higher speeds, Pulfrich suggested the perceived trajectory becomes asymmetric.

The proposed mechanism explains the alteration in perceived distance of an object moving horizontally across the field of vision, a type of motion demonstrated approximately in Pulfrich's first demonstration apparatus, and exactly in his second demonstration apparatus. However, particularly with the use of a pendulum, there is motion in both horizontal and vertical directions, and hence at the extremes of pendulum motion with larger amplitudes the vertical disparity may cause transient blurring or separation of the images depending on the angular displacement, size, and speed of the bob and the magnitude of the difference in perceptual latency between the two eyes (Joseph T. Lanska, MS, personal communication 2014).

Support and conflicts of interest

Drs. Lanska and Remler are supported by the US Department of Veterans' Affairs. The authors have no conflicts of interest to declare.

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