Title
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Judging the Speed of Pedestrians and Bicycles at Night

Introduction

Pedestrians and cyclists have little physical protection. Unlike the inhabitants of automobiles, they are not surrounded by rigid frames and such protective devices as airbags. Yet when pedestrians and cyclists share the roadway with automobiles, as they often do, the chance of collision with severe damage is high. In part, this is due to the great disparity of speeds involved. Pedestrians typically move quite slowly compared to the speed of automobiles, and the speed of bicycles is usually intermediate. Similarly, automobiles are much heavier and thus are capable of causing much more damage to the things with which they collide.

Another reason for the increased danger is the disparity in visibility, particularly at night. Automobiles have bright lights on front and back, with smaller side lights, making them highly visible in the dark. Bicycles may have only a weak headlight and nothing but reflectors on back and sides. The position in which the side reflectors are mounted on the wheel spokes is mandated by law. The Code of Federal Regulations (Ch. II, Section 1512.16, 1-1-00 Edition) specifies that street bicycles should have a reflector on each wheel, such that, "The center of spoke mounted reflectors shall be within 76 mm (3.0 in) of the inside of the rim. Side reflective devices shall be visible on each side of the wheel." (It does allow for reflective sidewalls or rims instead, but these are not common.) The position of the reflectors on wheel spokes is of interest and importance because it determines the path the reflector will follow when the bicycle moves in a forward direction. Although the frame of the cycle simply translates linearly across space, any point on a wheel other than its axle moves along a much more complex and thus longer path. A point on the rim of a moving wheel, for example, moves along the path of a cycloid, a combination of translation and rotation. Because the path of the reflector is longer than the path of the bicycle frame over the same translational distance, its average speed of motion will necessarily be greater. In addition, although the frame may move at a constant speed, the speed of lateral translation of the reflector will depend in part upon its position during the rotation of the wheel. When it is near the top of the wheel, it will move forward rapidly. When it is near the bottom, it will move forward slowly. Fig. 1 shows the cycloidal path that would be followed by a point on the rim of a rolling wheel.

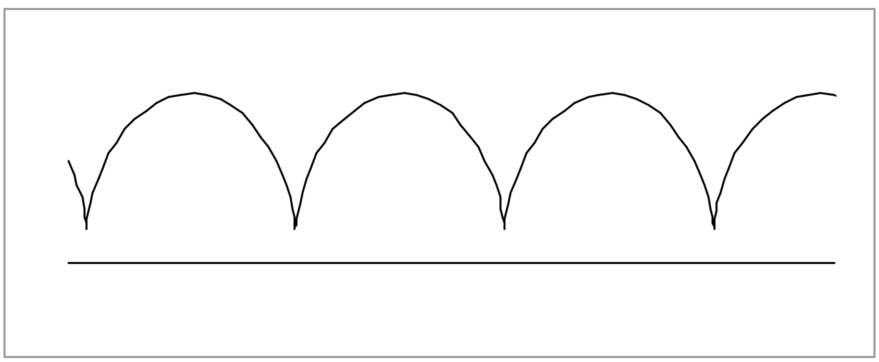

Figure 1. A cycloid, a combination of a translation and a rotation. This is the path that would be followed by the reflector on the rim of a rolling bicycle wheel.

Although the reflector—the most visible part of the bicycle at night—moves along the longer, more complex cycloidal path, the observer (an automobile driver, for instance) needs to know the velocity of motion of the frame, not the reflector. Surprisingly, no available models of speed coding by the visual system allow one to predict how an observer would perceive the translational speed of an object moving along the path of a cycloid. Thus, we have measured the apparent speed of one, two, or three objects in various configurations in which reflectors could be placed on a bicycle wheel.

Pedestrians who share the roadway with automobiles rely for visibility either on the reflective properties of their clothing and bodies, reflective surfaces added to shoes or clothing, or, increasingly, on small, flashing lights strapped to an arm or other body part. The ability of a driver to take appropriate evasive action to avoid a collision with a pedestrian depends upon his ability to see the pedestrian and judge his position and motion velocity. We are thus examining the ways in which various factors affect an observer's ability to perceive and judge the motion of a moving object. To date, we have measured the effect of the temporal flash (or flicker) frequency of a moving light (such as the flashing lights pedestrians sometimes wear) on an observer's ability to judge its translational speed of motion.

Methods

Cycloidal Motions. We determined the apparent translational speed of an object moving along a cycloidal path by displaying the object on a video monitor and asking an observer to compare its speed to that of a similar object moving along a straight path. The test stimulus was one or more white spots (0.3 deg, 5 cd/ m^2) on a dark background. Its direction of motion (leftward or rightward) was randomly determined on each trial, as was its position in the upper or lower half of the screen. The test stimulus motion was either linear (the control condition), one spot moving along a cycloidal path determined by its position on an imaginary wheel of 3.7 deg (visual angle) diameter, or two or three spots moving along paths determined by their respective positions on the same imaginary wheel. The translational speed of the wheel varied from 2 to 10 rad/sec.

The comparison stimulus was a similar white spot of constant luminance, moving linearly at a predetermined constant rate of speed during each trial. The direction (left-right) and screen placement (upper-lower half field) of the comparison stimulus were always opposite those of the test stimulus. Both the starting position and the total extent of travel were pseudorandomly determined on each trial to prevent observers' using relative times of crossing the midline or completing the presentation as a cue.

The observer's task on each trial was to signal which of the two stimuli, test or comparison, appeared to translate across the screen faster. No feedback was provided. In a given session, the translational speed of the test stimulus was predetermined, chosen from a set of speeds corresponding to 2 to 10 rad/sec of the imaginary wheel. The speed of the comparison stimulus was determined on each trial based on an adaptive staircase method. Each data point is based upon at least 5 such staircases.

Flashing Light. To determine the effect of temporal flashing (flicker) on the apparent speed of a moving object, we used a method similar to that described above. Observers judged the relative apparent speeds of two small lights moving in opposite directions across a video monitor. Methods and conditions were identical to those described above, with the following exceptions. The test stimulus always moved along a straight path, but its luminance was not constant over time. It flashed on and off as it moved, at temporal frequencies of 0 (control), 2, 4, 8, or 16 Hz. Its translational speed on a given trial was 4, 8, 16, or 32 deg (visual angle) sec^{-1}. During the 'off' intervals, although the test spot was not visible, the motion continued at the same rate. Thus, the spot reappeared farther along the path than the position at which it had disappeared. The flicker had a square-wave profile; thus, the spot was either at full luminance or was invisible at any given instant.

As before, the observers' task was to determine which of the two stimuli, test or comparison, moved at a higher rate of speed.

Results

<u>Cycloidal Motions.</u> Earlier (see De Valois, Takeuchi, and Disch, 2002; Disch, Takeuchi and De Valois, 2002) we reported that a single object moving along a cycloidal path appears to move across the screen (i.e., translate laterally) more rapidly than does a similar object moving along a straight path. We also found that adding a second object at the center of rotation (as though it were on the axle of the wheel) shifts the apparent speed in the opposite direction. The matching speed then becomes significantly lower than the actual translational speed of the wheel. Below are shown data from a range of different test stimulus configurations. These are illustrated below the horizontal axis of the figure. The ratio of the matching speed to the actual translational speed of the imaginary wheel is shown on the vertical axis. The two sets of points show data from two translational velocities of the test stimuli. Although these data are from a single subject, data from other subjects are similar.

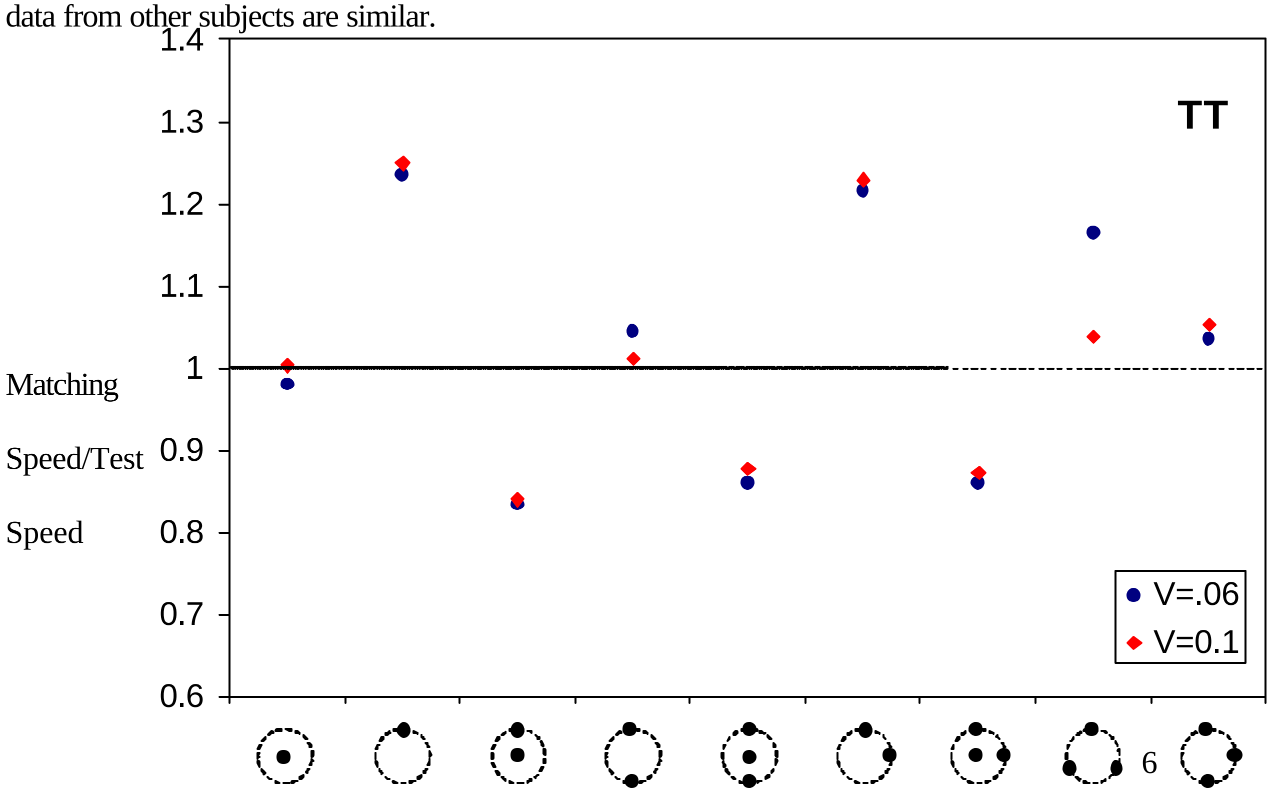

Fig. 2. The ratio of matching speed to actual translational speed of the test stimulus. The drawings below the figure illustrate the test stimulus configuration in each case. The imaginary wheel, here shown by dashed lines, was not visible.

These data show several interesting properties. First, when the two stimuli to be compared both move along a straight path (leftmost condition), observers can accurately judge their relative speeds. This configuration is equivalent to having a single reflector mounted on the axle of a wheel. Second, when a single test spot moves along a cycloidal path, it appears to move considerably faster than a similar spot moving along a straight path. This is shown by the second configuration and is similar to the case of a reflector mounted on a wheel rim. Third, when an additional spot is added at the center of rotation of the imaginary wheel (e.g., the third, fifth and seventh configurations above), the matching speed drops to a value considerably lower than the actual translational test speed. This indicates that the combination of a linearly-moving object on the imaginary axle and one or more other objects moving in a cycloid path around the axle will be seen as moving more slowly than its actual speed. The only configuration of objects moving along cycloidal paths that was reliably perceived as moving at its actual translational speed was a pair of spots placed directly opposite one another (configuration four above). This is equivalent to the case of two reflectors mounted directly opposite one another on the spokes of a wheel.

Flashing Lights. When a light flashes off and on as it moves, an observer's judgment of its translational speed can be significantly affected. For example, when the translational speed of the object's retinal image is 4 deg/sec, flickering the light can either have little effect on its apparent speed of translation (at low rates of alternation) or increase substantially (at high alternation rates). Fig. 3 shows data from three observers, two of whom (LP and JD) were naïve concerning the purpose and the ongoing results of this study. Note that at the lowest alternation rate (2 Hz), the observers make relatively small errors. (In this chart, a value of 1 on the y axis represents a veridical match between the speeds of the test and comparison objects.) However, as the alternation rate increases, the magnitude of the errors increase. Two subjects show their largest mismatches at an alternation rate of 18 Hz; the third has a greater error at 8 Hz.

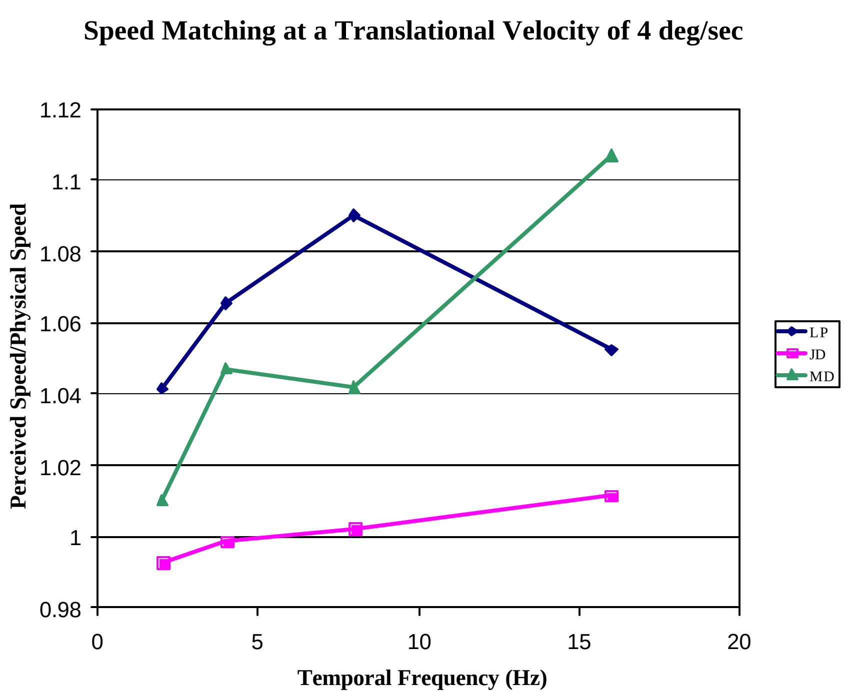

Fig. 3. Speed matching when the flashing test stimulus moves at 4 deg/sec. Note that the errors generally become larger as the alternation rate increases.

Figures 4, 5, and 6 below present data for conditions in which the test objects moved at 8, 16, or 32 deg/sec, respectively. There is an interaction between translational speed and rate of alternation, but the same general trend appears throughout. When the test object flashes on and off more rapidly, the perceptual overestimate of the object's speed tends to increase.

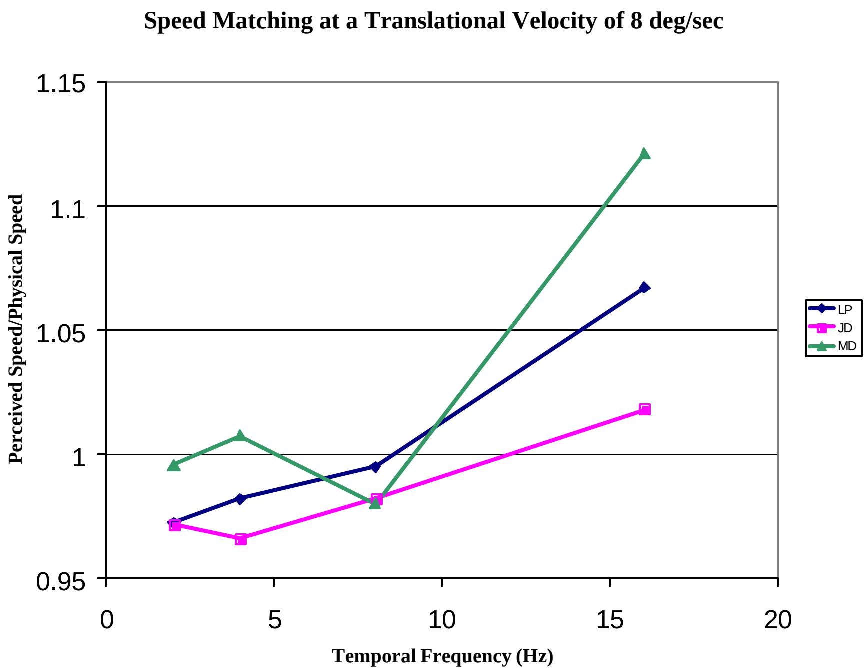

Fig. 4. Speed matching when the flashing test stimulus moves at 8 deg/sec. Note that the errors generally become larger as the alternation rate increases.

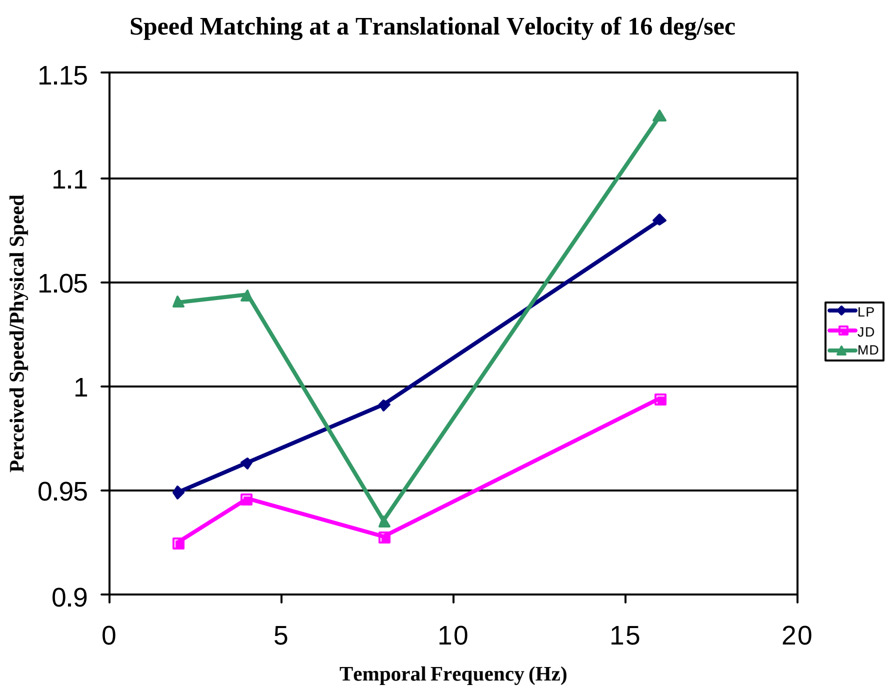

Fig. 5. Speed matching when the flashing test stimulus moves at 16 deg/sec. Note that again the errors are large at the highest alternation rate.

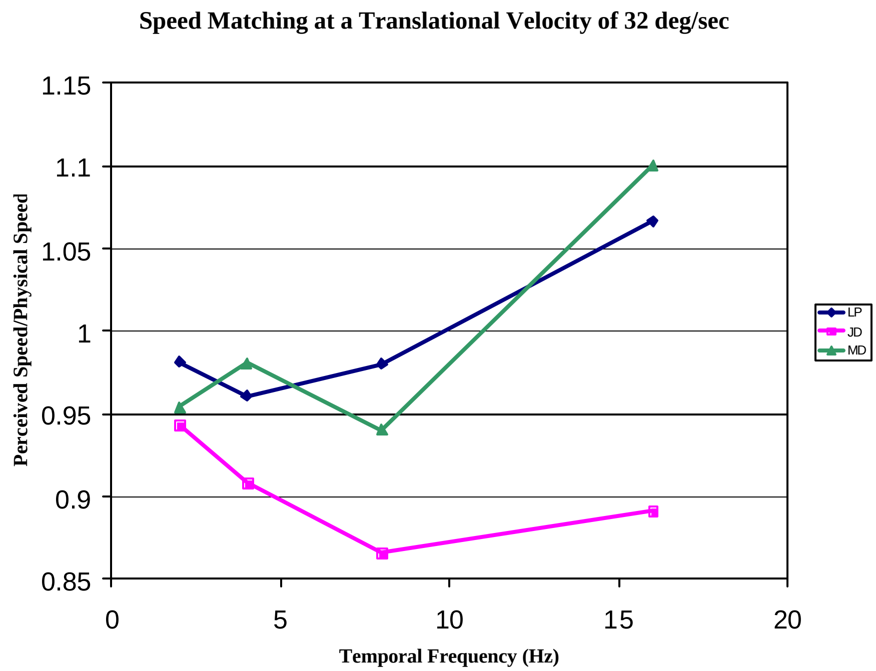

Fig. 5. Speed matching when the flashing test stimulus moves at 32 deg/sec. In this case, two observers continue to show the largest error when the flash alternation rate is highest. The third observer (JD), at this rapid rate of motion, underestimates the test object's speed when it flashes at any tested alternation rate greater than 2 Hz.

Discussion

Cycloid Motions. The results presented here raise questions concerning current federal regulations governing reflector placement on bicycle wheels. Our earlier data (Disch, Takeuchi, and De Valois, 2001; De Valois, Takeuchi and Disch, 2002) demonstrate that a single reflector mounted on the spokes of a wheel could lead to significant overestimation of the translational speed of the wheel (and thus the bicycle of which it is part). To the extent that automobile drivers determine whether evasive action is required based on their judgment of the velocity of a bicycle, the substantial perceptual errors found pose a danger. A driver approaching an intersection, for example, might erroneously judge that a bicycle approaching on the intersecting street would clear the intersection before the automobile arrived. A failure to brake in that situation could lead to a preventable collision.

The explanation for the perceptual anomalies observed is not clear. It is known that the perception of the trajectory of a point on the rim of a rolling wheel is often misperceived (e.g., Wallach & O'Leary, 1985; Isaak & Just, 1995), particularly when other points on the rolling object are visible (Proffitt & Cutting, 1980). In that case, a cycloid (such as that shown above or the slightly flattened prolate cycloid of a reflector on a wheel's spoke) will be perceived as though it were a curtate cycloid similar to that shown in Fig. 6 rather than the prolate cycloid (Fig. 7) which it actually follows.

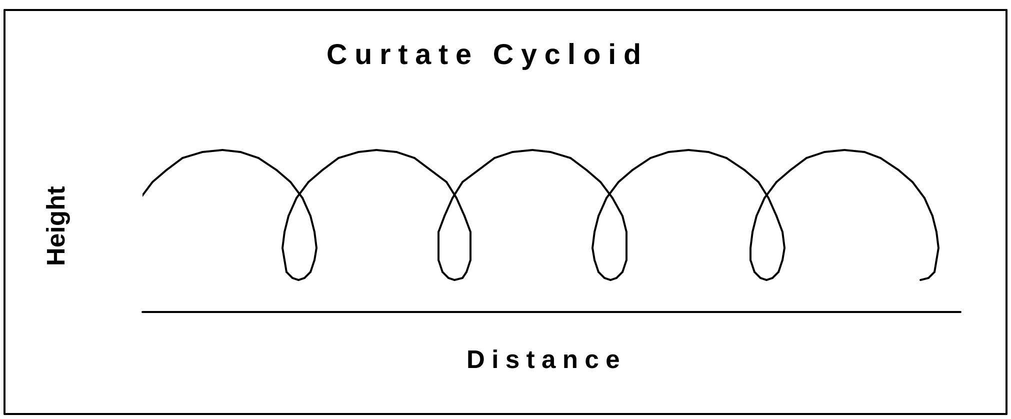

Fig. 6. A curtate cycloid, the *apparent* path of a reflector on the spoke of a rolling wheel.

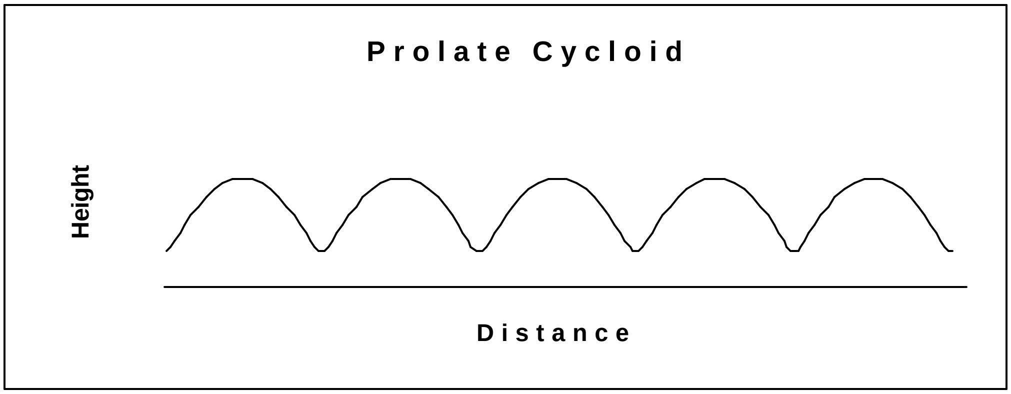

Fig. 7. A prolate cycloid, the *actual* path of a reflector on the spoke of a rolling wheel.

Current models of speed perception (e.g., Fennema & Thompson, 1979; Watson & Ahumada, 1985; Metha & Mullen, 1997) do not provide assistance. All model perception of the relative speed of simple patterns such as sinusoidal gratings. None addresses the question of how an observer might compute the translational speed of a discrete object from the variable speed of the object over a complex path. We are currently working to develop an appropriate model.

Before the model is completed, however, it is possible to make recommendations concerning the placement of reflectors on bicycle wheels. Current regulations require a single reflector to be mounted on the spokes of each side of each wheel, near the rim. As we have demonstrated, this configuration leads to substantial overestimation of the translational speed of the wheel. A simple solution would seem intuitively to be to mount the reflector on the axle, instead. One would then expect accurate speed estimation. However, that would entail a major cost. The unusual path traveled by a reflector on a bicycle spoke both captures the attention of an observer and allows a rapid identification of the object. These advantages should be retained, if possible. Thus, we would recommend placing two reflectors on each side of the wheel, mounted on spokes directly opposite one another and near the rim. Each of the two would follow the path of a prolate cycloid, thus capturing attention and allowing object identification. Further, our data show that observers can accurately judge the translational speed of the wheel with this configuration. This would retain the advantages of the current regulation while correcting the perceptual error produced by a single reflector mounted on the spokes.

<u>Flashing Lights.</u> The use of flashing lights on the arm of a pedestrian or a cyclist (or on the frame of a bicycle) has the great advantage of increasing visibility. Unlike a reflector, it does not depend upon an external light source, and the temporal flicker captures the attention of an observer. However, our data demonstrate that the rate of temporal flicker can substantially alter an observer's judgment of the translational speed of the object. The speed with which the image moves across the observer's retina interacts with the flicker rate to determine perception, but retinal image speed is not amenable to modification. It depends both upon the actual speed of the moving object (a pedestrian, say) and the distance between the object and the observer. Thus, the only factor that can potentially be modified is the flicker rate of the light.

The data presented above show that at flicker rates below about 8Hz, the perceived speed can be either higher or, occasionally, lower than the actual translational speed. However, when the flicker rate is high (e.g., 32 Hz), the observer's perception of object speed is generally higher than the real speed. The error tends to be substantial, often greater than 10%. A judgment error of this magnitude could significantly increase the likelihood of a pedestrian-automobile collision.

We are aware of no model that would explain these data. However, some possibilities are clear. The flicker waveform used in these experiments was a square wave. The power spectrum of a square wave include a major component at the fundamental frequency (the flash frequency reported here), with decreasing power at each odd integral harmonic frequency. Most modern models of speed perception (*vide supra*) are based on the existence of a few (three, say) mechanisms with differing temporal frequency tuning characteristics. There are also believed to be non-directional temporally-tuned mechanisms. If there is interaction among these, and that does not seem unlikely, then it is entirely reasonable to expect that flickering a moving light might affect its apparent speed. We are currently working on such a model.

As with the perception of a cycloid, however, practical recommendations can be made without waiting for fuller understanding of the underlying mechanisms. The data presented above demonstrate a substantial difference between speed perception at low flicker rates and high flicker rates. At low rates of flicker, there is relatively little effect on the perceived speed. It may be slightly higher or slightly lower than the actual object speed, but the difference is generally small. As the flicker rate increases, however, the perceptual error tends to increase. Given the need for accurate perception of the speed of a moving pedestrian or cyclist, the best solution would be to use a light with a low rate of flicker. Our data suggest that 2 Hz would be good. A slowly flickering light retains the advantage of capturing the attention of an observer, but it has little effect on the perception of its translational speed. In experiments yet to be carried out, we will determine whether the temporal waveform of the flicker is important and, if so, attempt to find the optimal waveform.

Summary

Psychophysical studies using objects on simulated moving wheels show that observers substantially overestimate the translational speed of a single light following the prolate cycloidal path of a reflector on a bicycle wheel. The addition of one or more other lights can either increase or decrease the perceived speed. The configuration that produces the most accurate speed perception without sacrificing visibility and attention appears to be two spots arrayed directly opposite one another on the spokes of a wheel. We thus recommend that bicycles have two reflectors mounted on each side of a wheel, positioned directly opposite one another.

Studies of the apparent translational speed of a flashing light moving along a straight path have shown that its translational speed tends to be overestimated if the flash (or flicker) rate is high. A flicker rate of 2 Hz serves to capture an observer's attention without having a significant effect on perception of the light's translational speed. We recommend, thus, that portable lights mounted on armbands or bicycle frames be set to flicker at 2 Hz and not more rapidly.

Acknowledgements

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