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Abstract

Mach bands are illusory bright and dark bands seen where a luminance plateau meets a ramp, as in half-shadows or penumbras. Ratliff, Milkman, and Kaufman (1983) showed that Mach bands are attenuated by placing stimuli, such as bars, nearby. An experiment comparing Mach band attenuation for bar and Craik-O'Brien stimuli shows that they are equally effective in attenuating Mach bands. The results suggest that the high-frequency components of a stimulus adjacent to a ramp are responsible for the attenuation. The findings are interpreted in terms of a recent filling-in model of brightness perception and the results of computer simulations of stimuli used by Ratliff et al and the present experiment are shown.

Key words: Mach bands, brightness, filling-in

Running head: Mach band attenuation by adjacent stimuli
1 Introduction

Mach bands are illusory bright and dark bands seen where a luminance plateau meets a ramp, as in half-shadows or penumbras. Regions of equal luminance appear to be differently bright, i.e., the distribution of perceived brightness deviates strikingly from the distribution of luminance. Mach (1865) hypothesized that the bands that now carry his name originated from distance-dependent interactions occurring in the retina. In effect, Mach anticipated several themes of contemporary vision science, such as lateral inhibition and the processing of contours. Mach also pioneered the use of linking propositions (Teller, 1980, 1984) in vision to link perceptual and physiological states. Since his work, several theories have attempted to explain Mach bands. See Pessoa (1995) for a recent review. For translations of Mach’s original papers and a review of subsequent work by others see Ratliff (1965); later research was reviewed by Fiorentini (1972).

Ratliff and colleagues (Ratliff, Milkman, and Kaufman, 1979; Ratliff, Milkmann, and Rennert, 1983; Ratliff, 1984) followed Mach’s (1906) idea of investigating the appearance of Mach bands by altering the spatial pattern of illumination adjacent to them. Their main finding was that the appearance of Mach bands was modified by placing stimuli, such as a bars, nearby. In fact, for certain stimulus conditions the bands disappeared altogether. Figure 1 shows a 1-D cross section of the main luminance profiles used by Ratliff et al (1983). Most of the adjacent stimuli were bars varying in direction of contrast, amount of contrast, proximity to the inflexion points of the ramp, and width. Biphasic bar stimuli, as well as triangular and Gaussian shaped stimuli were also employed.

The findings of Ratliff et al (1983) can be summarized as follows: a) A bar stimulus placed near either inflection point attenuates the adjacent Mach band that is normally perceived at the inflection point; if the bar is positioned close enough no Mach band is perceived. b) A bar far away from the inflection point has no effect on Mach band appearance. c) Attenuation is largely independent of the width of the adjacent bar stimulus. d) Attenuation is largely independent of the sign of contrast of the bar. e) A triangle-shaped stimulus near the inflexion point enhances the nearby band; as the stimulus is moved and its associated Mach band approaches the stationary Mach band in the ramp pattern, one induced band fuses with the other and produces an enlarged Mach band. The enhancement occurs as long as both Mach bands are of the same polarity (light or dark). In the case where they have opposite contrasts they attenuate each other. f) A truncated Gaussian stimulus with the same area as a bar stimulus that attenuates a Mach band and that of a triangular stimulus that enhances a Mach band has little or no influence on its appearance. In summary, the three main features of the interfering stimuli are proximity, contrast, and sharpness.

Ratliff (1984) extended the results of Ratliff et al (1983) by using biphasic bars (see Figure 1C) positioned in the middle of the luminance ramp. Since the attenuation results observed by Ratliff et al (1983) did not extend beyond around 15 arcmin, he employed a very narrow ramp (15 arcmin). He showed that as the contrast of the biphasic bar was increased both light and dark band width decreased.
Figure 1: Cross sections of the patterns (A–F) employed by Ratliff et al. (1983) to study the effect of adjacent stimuli on Mach bands. Bars of sufficient contrast and sufficiently close to the ramp inflection point destroyed the adjacent Mach band. A triangular shaped adjacent stimulus (D) enhanced Mach bands, while a Gaussian shaped stimulus (E) had little or no effect.
2 Mach Band Attenuation by Adjacent Craik-O’Brien Stimuli

A filling-in model of brightness perception was recently presented that accounts for Mach bands and other stimuli by employing boundary computations that are sensitive to luminance steps as well as luminance gradients (Pessoa, Mingolla, and Neumann, 1995). Abrupt luminance transitions (e.g., steps) produce strong, localized, boundaries, through contrast enhancement. According to the model, any stimulus adjacent to a ramp inflection point capable of generating a sharp boundary, would annihilate the associated Mach bands if positioned close enough. Thus the model predicts that an adjacent Craik-O’Brien cusp should attenuate Mach bands. It also predicts that the effects of Craik-O’Brien and bar stimuli should be similar. For example, as long as the cusp contrast is high enough (to trigger a sharp boundary signal), attenuation should occur more or less independent of the width of the cusp. Moreover, the polarity of the cusp should not be important. The present experiment tests whether stimuli based on the Craik-O’Brien cusp luminance distribution attenuate Mach bands, thereby testing a critical prediction of the filling-in model. The use of half-cusps provides a way to determine the distance between the Craik-O’Brien adjacent stimulus and the ramp that is equivalent to the one when bar stimuli are used (see Figure 2).

It is interesting to note that Ratliff et al (1983) suggest that an experiment should be performed in order to investigate whether the high spatial frequency content of a step-edge is responsible for the attenuation effect. In effect, the Craik-O’Brien cusp is composed of such high frequency components (see, e.g., Burr, 1987).

2.1 Methods

Ratliff et al (1983) report that the attenuation of Mach bands is largely independent of sign of contrast, i.e., they found similar attenuations for the stimuli in Figure 1A and 1B. However, the simultaneous contrast effect (border contrast) of a bar with the adjacent luminance plateau can interact with the perception of the Mach band, as noted by Ratliff et al (1983, p. 4556) for the case of stimuli A and B in Figure 1: “Most observers reported that the dark (negative) border contrast of a bar with positive contrast sometimes tended to “attract” and to fuse with the dark band when the bar was nearby [Figure 1B]. On the other hand, the bright (positive) border contrast of a bar of negative contrast sometimes tended slightly to “repel” and to stay separate from the dark Mach band when the bar was nearby [Figure 1A].” They report similar, but inverse, effects for the case of the light Mach band. In the present experiment, Mach band attenuation was measured, as done by Ratliff et al (1983), by assessing the width and location of the bands. Pilot studies confirmed the above remarks by Ratliff et al, and showed that subjects can find the task very difficult in cases where “attraction” occurs. Thus only adjacent stimuli contrasts that tended to “stay separate from the Mach bands” were used (Figure 2). The measured width is due, therefore, primarily to the luminance ramp pattern and not to potential fusion effects associated with the contrast of the adjacent stimulus.

Figure 2 shows a few of the stimuli used in the experiment. Three types of adjacent stimuli were used: bars (10 arcmin), narrow cusps (7 arcmin), and wide cusps (20 arcmin). The
narrow and wide cusps had smaller and larger stimulus areas, respectively. The wide cusp was designed so as to have the same overall area of a bar stimulus. A total of 26 experimental patterns were used: 3 adjacent stimuli (bar, narrow cusp, wide cusp), 4 distances (0, 3, 6, 15 arc min), and 2 band types (interfering stimuli adjacent to light Mach band and to the dark Mach band). Regular luminance ramps were also presented and served to measure light and dark bands (2 stimuli) without adjacent stimuli. A total of 5 repetitions for each stimulus was used.

The same method used by Ratliff et al (1983) was employed to measure the width and location of the Mach bands. Figure 3 shows all display regions and associated luminances. The coupled pointers were manipulated through two dials used to input the leftmost location of the band and the band width. Once confident of both width and location of the band, the subject recorded his or her settings by pressing a mouse key.

The luminance values used were approximately the ones used by Ratliff et al (1983). The Michaelson contrast between the adjacent stimuli (when present) and the plateau region containing it was 15%. The luminance of the pointers was such that they had 15% contrast above the higher plateau or 15% contrast below the luminance of the lower plateau, depending on whether the adjacent stimulus appeared near a high luminance inflection point or a low luminance inflection point, respectively. In all, the set-up and ramp definition followed closely the ones used by Ratliff et al (1983). It should be stressed, however, that the results do not critically depend on these specific values and can be obtained with several other settings. The most critical parameter is the width of the ramp, which subtended 25 arcmin in the experiment.

Five subjects, including the author, participated. All had normal or corrected-to-normal vision. Except the author, subjects were naive concerning the purposes of the experiment.

2.2 Results

Measurements of Mach bands can vary widely across subjects (Ratliff, 1965). In the present experiment results were similar for all 5 subjects and are shown in Figure 4 for 2 individual subjects.

Figure 4 shows perceived Mach band width as a function of the distance of the adjacent
Figure 3: Schematic representation of the set-up employed to display and measure Mach band position and width. The luminance of the plateaus and of the patches above and below are given in ft.-L. The luminance of the pointers varied with the contrast of the adjacent stimulus (see text). The ramp width was 25 arcmin.

stimulus from the low or high luminance inflection points. As the distance increased, both band types increased in width; distance was significant for all subjects ($p < 0.001$). At a distance of 15 arcmin, interfering stimuli had little or no effect on Mach band width as can be seen from the width of the bands when the luminance ramp was presented alone (see stars). Two groups of curves can be seen, one for light Mach bands, the other for dark Mach bands; band type was significant for all subjects ($p < 0.001$). Note however that for both light and dark bands, the type of adjacent stimulus had no effect on perceived width; for all subjects adjacent stimulus shape was not significant ($p > 0.05$).

The results shown in Figure 4 lend further support to the claim of Ratliff et al (1983, p. 4557) that “the most important feature of an effective stimulus is a sharp edge.” In other words, the results suggest that the high-frequency components of an adjacent stimulus are responsible for Mach band attenuation. A narrow cusp of about 7 arcmin was as effective as a wide cusp of slightly more than 20 arcmin or bar stimulus of 10 arcmin. These findings are also in line with results by Ratliff et al (1983) that showed that Mach band attenuation was independent of the width of the adjacent stimulus.

Mach band attenuation due to Craik-O’Brien stimuli is consistent with the filling-in model of Pessoa et al (1995). In the next section, model simulations are presented which illustrate its behavior when processing both bar and Craik-O’Brien stimuli.

1 Multi-way analyses of variance (ANOVA) were performed for each individual subject.
Figure 4: Averaged results of the Craik-O’Brien adjacent stimulus experiment for two individual subjects. Mach band width is plotted as a function of the distance from corresponding inflection point. Stimuli adjacent to the high luminance inflection point are indicated by the word “high” on the lines above the graphs, and stimuli adjacent to the low luminance inflection point are indicated by the word “low.” Two groups of curves can be observed, one for light Mach bands, one for dark Mach bands. Stars denote light and dark Mach band without adjacent stimulus. Error bars denote ±1 standard error.
3 Simulations of the Filling-in Model

Filling-in models propose that spreading of neural activity within filling-in compartments produces a response profile isomorphic with the percept (Fry, 1948; Walls, 1954; Gerrits and Vendrik, 1970; Davidson and Whiteside, 1971; Hamada, 1984; Cohen and Grossberg, 1984; Grossberg and Todorovic, 1988; Grossberg, 1994). Traditionally it has been assumed that filling-in models cannot account for Mach bands (e.g., Kingdom and Moulden, 1992, p. 1579; Blomnaert and Martens, 1990, p. 27). One reason is that filling-in as specified by boundary-gated diffusion has been functionally interpreted to mean “averaging between edges” — i.e., the final equilibrated output is constant. This is certainly a possible outcome produced by filling-in models. However, the emphasis of such models is in the role of contours, or boundaries, in determining visual surface perception. Whether “brightness” is completely uniform or not within such regions is not the central issue.

A recent filling-in model of brightness perception was presented that accounts for Mach bands and other stimuli by employing boundary computations that are sensitive to luminance steps as well as luminance gradients (Pessoa et al, 1995). Following the proposal of Neumann (1993, 1994), two processing channels were proposed, a contrast-driven and a luminance-driven channel. The four main computational stages of the model are: 1) The input stimulus is decomposed into separate contrast-driven and luminance-driven representations. 2) Contrast-driven signals from ON/OFF center-surround filtering are employed to produce boundaries. 3) Contrast-driven signals are also used as feature signals that undergo boundary-regulated diffusion. 4) Contrast-driven and luminance-driven signals are recombined providing the final model output.

When processing a luminance ramp, spatially extended boundary signals of sufficient amplitude are generated which are able to “trap” the overshoots and undershoots present in the feature signal, producing Mach bands (see Figure 5). Note that filling-in contributes only to the production of the light and dark bands and that the ramp modulation originates from the luminance-driven channel. For a luminance step no Mach bands are generated since the boundary computations produce a localized signal (at the edge) that allows the diffusion of the overshoot and undershoot, thereby uniformizing the brightness distribution around the edge (see Figure 6). The strong localized boundary signal is generated due to the abrupt luminance transition which triggers feedback sharpening.

The filling-in model predicts that Mach bands are the result of the trapping of overshoots and undershoots by boundary signals. If, by some mechanism, the boundary signals associated with the ramp inflection points could be removed, Mach bands should not occur, according to the model. The boundary circuit produces two types of boundary signal distributions for a given region of space: sharp or spatially extended (see Figures 5 and 6). Abrupt luminance transitions that produce sharp boundaries are such that no surviving boundary activity remains in the vicinity of the step — an extreme case of contrast-enhancement. This is illustrated in Figure 7 where a “missing fundamental”2 stimulus is input to the system. The abrupt luminance transitions generate sharp boundary signals while low-intensity signals remain only some distance away from the edges of the stimulus.

2A missing fundamental is equivalent to a square wave luminance modulation with the fundamental Fourier component removed.
Figure 5: Filling-in model with contrast- and luminance-driven channels processing a luminance ramp. (A) Luminance ramp. (B) Contrast-driven signals from ON and OFF filtering. (C) Luminance-driven "low-pass" signal. (D) Boundary signals. (E) ON (top) and OFF (bottom) filling-in (equilibrated). (F) Final brightness.

Figure 6: Filling-in model applied to a luminance step. The same stages as in Figure 5 are shown. The ON and OFF adjacency of filtering responses (B) leads to the formation of strong localized boundaries. Filling-in in the ON and OFF channels can proceed freely.
The behavior of the boundary circuit can be used to account for Mach band attenuation by adjacent stimuli, as studied by Ratliff and colleagues and in the present paper. Figure 8 shows computer simulations of the filling-in model using some of the stimuli used by Ratliff et al (1983). For a luminance ramp without adjacent stimuli, the boundary signals at the inflection points are able to register light and dark bands (Figure 8A) through the trapping of filtering overshoots and undershoots (see Figure 5). Proper boundary signals are also able to register the bands when an adjacent bar is placed far enough from the ramp inflection point (Figure 8C). Light and dark Mach bands placed alongside the bar are predicted. As discussed, subjects report the presence of the two bands, with the width of the dark Mach band being similar to the one produced by a regular ramp stimulus. Note that the model predicts the same brightness level for the dark band in both cases but that the presence of the bar produces a slightly more pronounced dark bar due to a small simultaneous contrast effect in the region surrounding the bar. When a bar is close to the low luminance inflection point (Figure 8B), the spatial sharpening of the boundary signals associated with the left edge of the bar will not allow the signals usually produced by the ramp inflection to survive. The model correctly predicts that no dark Mach band is seen — only a light one. A similar behavior also applies to a bar of opposite polarity and a biphasic bar, as well as for stimuli adjacent to the high luminance inflection point (light Mach band). The important feature is that the bar stimulus have enough contrast in order to trigger spatial sharpening. In that case, feedback sharpening will destroy the boundary signals capable of trapping the signals associated with the bands.

The three main features controlling the stimuli that attenuate Mach bands can also be explained. Proximity is required so that the spatial sharpening that is triggered by the closest edge of the bar be able to remove the (adjacent) boundary signals capable of producing the bands. Contrast needs to be high so that spatial sharpening is triggered in the first place. Sharpness is required since the boundary circuit only contrast enhances abrupt luminance transitions. Other stimulus characteristics can also be explained. First, the width of the bar is not important. The important variable is the distance of the closest edge of the bar to the ramp. Second, although contrast is important, polarity of contrast is not. Boundary signals are independent of polarity of contrast and both light and dark bars of high enough contrast will induce boundary sharpening and eliminate Mach bands.

Ratliff et al (1983) report that Mach band width increases monotonically and gradually with the distance of the adjacent stimuli. Simulations of the filling-in model also display such behavior. Figure 9 shows the extremes cases where no Mach band is seen (very close bar) and the case where it is seen (no adjacent stimulus is present) together with a Mach band of
Figure 8: Computer simulations of the filling-in model. (A) Luminance ramp (no adjacent stimulus). (B) Dark bar near luminance ramp. (C) Dark bar far from luminance ramp. See text for discussion.
intermediate width when the adjacent stimulus is at an intermediate distance.

Figure 9: Computer simulations of the filling-in model. Mach band width depends on the distance of the adjacent stimulus. Thin lines show simulations for a ramp without an adjacent bar (wide Mach band) and for a bar far from the inflection point (also wide Mach band). An adjacent bar at an intermediate distance produces a band of intermediate width (thicker line).

The prediction of the filling-in model that Craik-O'Brien stimuli should attenuate Mach bands in a way similar to bar stimuli was confirmed in the experiment above. Figure 10 illustrates the results of a computer simulation when a half-cusp adjacent stimulus similar to the one used in the experiment is presented to the model. A half-cusp of high enough contrast will trigger spatial sharpening in the boundary circuit, destroying the boundaries responsible for the dark band. The cusp eliminates the dark Mach band in the same manner as a bar does (compare with Figure 8B).

Figure 10: Simulation of the filling-in model with a half-cusp adjacent stimulus. No dark Mach band is produced. The boundary signals immediately to the right of the sharp boundary register the Craik-O'Brien half-cusp.

4 Discussion

The standard textbook account of Mach bands postulates that the input waveform is transformed by lateral inhibition in the retina producing both overshoots and undershoots in the filtered distribution that are associated with light and dark bands, respectively. Such an account predicts that Mach bands should be maximal at luminance steps. In the past 15 years, it
has become clear, however, that Mach bands are weak, if existent at all, at steps. Ross, Holt, and Johnstone (1981) varied the spatial frequency of trapezoidal waves and showed that for frequencies above 2 c/deg Mach bands were not visible. The investigation of Ross, Morrone, and Burr (1989) also measure Mach band strength as a function of spatial frequency, revealing an “inverted U” behavior where ramps of intermediate width were optimal. Both narrow and wide ramps decreased Mach band visibility. The two results above can be translated into a minimal ramp width eliciting Mach bands of around 4–7.5 arcmin.

In the past two decades several models have attempted to explain Mach bands by supplementing lateral inhibition (i.e., simple filtering) by either more sophisticated filtering schemes, or other mechanisms (e.g., interpretation rules). Three classes of models can be identified (Pessoa, 1995): a) feature-based; b) rule-based; and c) filling-in. Feature based theories postulate that edges and lines are basic primitives of early vision. Specific proposals are the Edge-bar inhibition scheme (Tolhurst, 1972), the Local Energy model (Morrone and Burr, 1988; Burr and Morrone, 1992), the Cell assembly model (du Buf, 1994), and the filtering scheme of Fiorentini, Baumgartner, Magnussen, Schiller, and Thomas (1990). They differ in the ways primitives are detected and how the detection operators — i.e., even- and odd-symmetric mechanisms — interact (competition or cooperation), but postulate that Mach bands are the result of lines being signaled at the inflection points of luminance ramps. Rule-based theories may also employ primitive features, but what distinguishes them is a stage of brightness description by the application of a fixed set of rules interpreting what the initial filtering responses map to. Two proposals are MIRAGE (Watt and Morgan, 1985) and MIDAAS (Kingdom and Moulden, 1992). Finally, filling-in theories propose that the spreading of neural activity within filling-in compartments produces a response profile isomorphic with the percept (e.g., Grossberg and Todorović, 1988; Pessoa et al, 1995).

A major conceptual difference exists between feature-based and ruled-based theories on the one hand, and filling-in theories on the other. According to the former, one of the main tasks of the visual system is to detect salient features (e.g., lines and edges). Most of the “detail” in scenes (e.g., luminance gradients) is ignored. The latter theories attempt to build representations that preserve the geometric structure of percepts. An analog mode of representation is favored through the use of spatially organized fields of activity. See Todorović (1987) and Ratliff and Sirovich (1978) for related discussions.

Tolhurst (1972) proposed that two competing mechanisms are responsible for the appearance of Mach bands, one which generates them and one which attenuates them. He proposed that bar and edge detectors — i.e., odd- and even-symmetric operators — could be identified with these mechanisms, respectively. More specifically, edge and bar operators inhibit each other in a spatially limited form. For a regular luminance ramp, the optimal edge responses at the middle of the ramp are far removed from the bar responses that respond strongly at the inflection points. Mutual inhibition cannot affect the responses and light and dark bands ensue. This account also explains why Mach bands are not seen at a step. For this luminance distribution, both edge and bar detectors located near the step will respond. Since the edge detectors are maximally activated they will suppress the smaller activity of the bar detectors. No Mach bands are seen.

Ratliff (1984) set out to directly test this idea by positioning a biphasic bar in the middle of a narrow luminance ramp. According to Ratliff, the variable contrast biphasic bar would
provide independent control of the strength of the two competing mechanisms. High contrast biphasic bars would produce strong responses from odd-symmetric operators in the middle of the ramp and strong attenuation of the bands. For low contrast biphasic bars, the weak inhibition from the bars would not be able to remove the bands. His finding was that as the contrast of the biphasic bar was increased light and dark band width decreased. The results were taken as evidence that some version of Tolhurst's scheme was correct.

However, the Tolhurst-Ratliff proposal is not consistent with the fact that both regular bars and biphasic bars attenuate Mach bands in a similar form. While biphasic bars more strongly activate odd-symmetric, or edge, operators, regular bars more strongly activate even-symmetric, or bar, operators. Thus, regular bars should not attenuate Mach bands. The Tolhurst-Ratliff proposal also encounters problems explaining why the width of the adjacent stimulus is not important. Narrow bars should strongly activate only even-symmetric mechanisms, while wider ones produce stronger responses from high spatial frequency odd-symmetric cells (locally the adjacent stimulus will be an edge). Finally, the half-cusps employed in the current experiment also activate bar detectors more strongly than edge detectors and therefore, according to the Tolhurst-Ratliff scheme, should not attenuate Mach bands.

The proposal of Pessoa et al (1995) suggested that Mach bands are due to boundary-gated filling-in in which ON and OFF filtering responses are contained by strong boundaries. In this framework, the mechanisms of Mach band generation and attenuation are not in competition as suggested by Tolhurst and Ratliff but, instead, correspond to the behavior of the boundary circuit and its interaction with filling-in. The mechanism that “generates” Mach bands is the production of spatially broad boundary signals that trap diffusive filling-in (Figure 8A). The mechanism that “attenuates” Mach bands is the spatial sharpening of boundaries resulting from abrupt luminance transitions (Figure 8B).

Two recent theories have provided alternative explanations for Mach band attenuation. MIDAAS (Kingdom and Moulden, 1992) employs interpretation rules to map filtering responses to brightness descriptions and attributes the attenuation to the combined effects of this process applied at multiple spatial scales. Preliminary simulations of the Cell assembly model (du Buf, 1994) show results consistent with the attenuation, although a more complete formulation of the model (e.g., multiscale interactions) is required before it can be properly evaluated. An evaluation of these and other models of Mach bands can be found in Pessoa (1995).

The present experimental results should be used in order to evaluate existing models of Mach bands. One difficulty is that with the level of complexity of the theories it is often difficult to establish the extent to which they can, in their present form, account for the experimental results. Simulations of the filling-in model have shown that it can account for the finding that Mach band attenuation is directly related to the high-frequency content of the adjacent stimulus.
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