On the Role of Color in the Perception of Motion in Animated Visualizations

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ABSTRACT

Although luminance contrast plays a predominant role in motion perception, significant additional effects are introduced by chromatic contrasts. In this paper, relevant results from psychophysical and physiological research are described to clarify the role of color in motion detection. Interpreting these psychophysical experiments, we propose guidelines for the design of animated visualizations, and a calibration procedure that improves the reliability of visual motion representation. The guidelines are applied to examples from texture-based flow visualization, as well as graph and tree visualization.

CR Categories: I.3.3 [Computer Graphics]: Picture/Image Generation; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture

Keywords: Color, luminance, motion detection, perception, human visual system, flow visualization, information visualization

1 INTRODUCTION

"The perception of dynamic patterns is less well understood than the perception of static patterns. But we are very sensitive to patterns in motion and, if we can learn to use motion effectively, it may be a very good way of displaying certain aspects of data."

Colin Ware [83], p. 230

The main goal of all fields of visualization and computer graphics (CG) is to produce images for a human observer. Therefore, visual perception has been playing an important role in the visualization and CG communities and will continue to do so. Utilizing the knowledge of the properties of the Human Visual System (HVS), researchers have enhanced rendering techniques by making them more effective and/or more efficient. An effective visual representation tries to achieve a specific visual sensation, which is particularly important for any visualization technique.

The goal of this paper is to provide assistance in improving the use of color in conjunction with motion. Here, we have to distinguish between the detection of patterns in motion (seeing their "existence") and the actual perception of motion (recognizing speed and direction of motion). The detection of moving patterns is quite well understood. Measured quantitative data for the corresponding Contrast Sensitivity Functions (CSF) is frequently used in perception-based rendering techniques (see references in Section 2). However, the sensation of motion is less well understood for color stimuli and, in particular, purely chromatic, isoluminant stimuli are extensively discussed in the psychophysics and neuroscience literature. Since motion perception can be impaired for color stimuli, it is a common assessment in the visualization and CG communities that color is irrelevant to perceiving how objects are moving [84]. We agree that this statement is useful as a general guideline. Nevertheless, we would like to shed light on some noticeable chromatic effects and propose a differentiated view on the perception of moving colored objects.

The contributions of this paper are: First, relevant results from psychophysical and physiological research are presented. Here, ample evidence is provided for an important role of color in motion detection. Second, the interpretation of results from psychophysical experiments leads to a proposal of some guidelines that assist the design of animated graphics. Third, it is inferred that a calibration is needed to represent data by the perceived speeds of colored patterns; and a corresponding calibration procedure is described for a desktop work environment. Finally, a few visualization applications are discussed to demonstrate how the guidelines and the calibration approach can be used.

2 RELATED WORK IN COMPUTER GRAPHICS AND VISUALIZATION

Various aspects of human visual perception are presented in a number of SIGGRAPH courses [13, 24, 27, 34, 75], IEEE Visualization tutorials [26, 42], and in a book by Ware [83].

Directly related to this paper is previous research on the effective use of motion for visualization. Since motion provides additional perceptual dimensions, such as phase, amplitude, or frequency of sinusoidal motion [43], these perceptual dimensions can be used in the visualization of multivariate data to display additional data dimensions. Motion is preattentive and allows moving patterns to pop out [60]. Therefore, motion can be used in the fast, preattentive visualization of complex data [31, 32] or for filtering and brushing techniques in information visualization [2, 3]. Also, motion can promote the perception of shape; this structure-from-motion effect is exploited by kinetic visualization [51], using moving particles.

Another line of research uses the knowledge of the HVS to improve the quality of displayed images, based on a photorealistic computation of illumination [25, 52, 64]. Quantitative quality measures are typically based on a CSF that depends on spatial frequencies of the image and additional viewing parameters. Examples for elaborated spatial and chromatic quality metrics are the Visible Difference Predictor (VDP) [17], Sarnoff's Just-Noticeable Difference (JND) model [50], or Rushmeier et al.'s models [70]. The spatiotemporal CSF [38] describes the detectability of moving patterns and is an important element in motion-aware metrics [58, 59]. Saliency models [35] simulate where people focus their attention in images to improve the efficiency of rendering [6, 23]. Of particular interest are models that take into account motion as part of the saliency computation [7, 89].

3 PSYCHOPHYSICAL AND PHYSIOLOGICAL RESEARCH

We briefly discuss some aspects of color vision and motion detection within the HVS. Detailed background information on neuro-

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science and human vision can be found in [33, 37]. Two categories of photoreceptors in the retina serve as detectors for light that is collected by the eye: rods and cones. Here, we consider only cones because they dominate the initial response at normal light levels. Cones can be classified as short-wavelength (S) cones, medium-wavelength (M) cones, and long-wavelength (L) cones. The responses of the S, M, and L cones are coded in terms of opponent color channels. The achromatic channel represents the intensity of light and reflects the sum of M and L cones. The red-green (RG) channel measures the difference of the L and M signals, the yellow-blue (YB) channel measures the difference between the sum of L and M signals and the S response.

The geniculostriate system (lateral geniculate nuclei, LGN) consists of two major pathways with distinct physiological properties: the color-opponent and the broad-band (achromatic) pathways, which remain separated through several cortical stages. Conventional views of visual perception propose that different visual capacities are connected to the different pathways. The "color-blind" (magnocellular) broad-band pathway provides motion information and the "motion-blind" (parvocellular) pathway conveys (opponent) color information [44, 91], i.e., the visual system's primary analysis of color and motion take place in parallel at different areas of the brain. Therefore, motion analysis would be compromised if color had to be analyzed before motion.

Numerous psychophysical experiments have been conducted to gain a detailed understanding of the HVS's motion-detection capabilities. In the following, results are presented that are relevant for the design of practical visualization techniques. The main parameters for psychophysical investigations are the type of stimulus that is presented to the human observer and the kind of task that has to be solved. Typical stimuli are sinusoidal gratings or random dot patterns that either move spatially or flicker temporarily. Two main tasks can be distinguished. The first task is the detection of motion to reveal thresholds for motion discrimination. Actually, two different sub-tasks with the same moving stimulus are performed to measure forced-choice contrast thresholds for stimulus detection (discrimination from blank field) and direction-of-motion detection. The motion discrimination threshold is then given as the ratio of the motion threshold to the detection threshold, i.e., the M/D ratio. The unit-free M/D ratio has the advantage that reduced cone contrasts under different stimuli conditions are cancelled out [62], i.e., the influence of the spatiotemporal CSF is absorbed. The second task is the detection of velocity magnitude. The perceived speed is usually described with respect to the speed of an achromatic stimulus [12].

In accordance with the aforementioned notion of separated motion and color pathways in the HVS, some psychophysical investigations show that motion perception of purely chromatic, isoluminant stimuli is degraded under some conditions. Ramachandran and Gregory [65] report a failure to perceive motion in RG random-dot kinematograms at isoluminance. Subsequent investigations support this point of view by demonstrating that the perceived speed of moving isoluminant stimuli is slower in comparison to that of luminance stimuli [12, 30, 44, 46, 56, 61, 79].

On the other hand, the loss of motion perception in color vision is not complete, especially for suprathreshold stimuli. Both the motion direction of drifting sinewave gratings and the frequency of flicker can be discriminated at contrasts close to, although not at, detection threshold [10, 19, 28, 56, 62]. Cropper [14] reports that, for suprathreshold chromatic contrast, both discrimination of motion direction and velocity magnitude improve to performance levels comparable to that of luminance gratings. In addition, there is an indication that a low-level motion-detection mechanism is prevalent at high contrast [15] and high speeds of isoluminant stimuli [73]. Experiments with combined motions of luminance and chromatic patterns also suggest that color plays a substantial role in motion perception [63]. Another indication for a chromatic contribution to motion detection is given by the motion aftereffect from isoluminant stimuli [11, 18, 55]. Furthermore, the motion-detection mechanisms of the HVS can identify even very brief signals, which shows that chromatic motion provides input for early stages of motion analysis [16]. Finally, neurophysiological experiments with primates indicate that there are mechanisms in the motion-detection pathway that have some (reduced) color sensitivity [45, 71].

In addition to the detection of motion direction, the perceived velocity magnitude of patterns plays an important role. As mentioned before, there is extensive evidence for color-induced apparent motion being slower than luminance-induced motion [12, 30, 56, 61]. The perceived speed of chromatic stimuli is strongly contrast-dependent [14, 56], compared to luminance stimuli (even luminance gratings, however, "slow down" at reduced contrasts [76]).

Some possibilities that would allow a chromatic stimulus to produce a response in the luminance mechanism of the HVS are discussed in the vision literature. This luminance effect would explain the aforementioned results within the concept of different pathways for motion and color. The possibility of luminance "artifacts" that directly originate in the stimulus (for example, from an inaccurate overall isoluminant point, from variations in individual cells' isoluminant points, or from chromatic aberration) is extremely unlikely [30, 57]. However, some psychophysical experiments indicate that chromatic stimuli can be contaminated by dynamic luminance artifacts (for example, nonlinearities in the responses to colors, or differences in the temporal phase of the neural response to the component colors) [57, 90]. Finally, Lu and Sperling [47, 49] propose a three-systems theory of human visual motion perception, where the third-order system has simultaneous access to inputs of form, color, depth, and texture. Third-order motion detection would be based on the analysis of moving features in a saliency map. Although attention may play a greater role for chromatic than for achromatic motion processing, there are other experiments with motion aftereffects which indicate that chromatic motion does not appear to rely more on attentional processing than achromatic motion does [66].

In general, it is not quite clear to what extent the different pathways in human perception can interact with each other; in addition to the issues discussed in this paper, there are numerous other phenomena that indicate manifold interactions between different elements of stimulus processing (see, e.g., Kandel et al. [37]).

4 Design Guidelines

We try to adapt the above psychophysical findings for the needs of visualization applications. Although there is not yet a well-established computational model that would describe all the previously mentioned results, we think that we can provide some useful guidelines for the application of color in animated computer graphics. The goal of psychophysical research is to gain a better understanding of the structure and properties of the HVS and therefore much effort is taken to clearly separate the influences on different pathways by choosing specifically designed stimuli (e.g., sinusoidal gratings). In contrast, visualization applications contain a variety of different visual objects and typically do not activate an isolated response within the HVS. To assist the design of effective and efficient rendering techniques, we combine and interpret the results of the aforementioned literature to propose some guidelines. The main goal is to stimulate an improved awareness for both the opportunities and limitations associated with moving color patterns. In accordance with a prevalent assessment in the visualization community, the first guideline is:

[G1] Use luminance contrasts for best motion perception.

Whenever possible, luminance signals should be applied to provide a reliable motion perception. It is a well-established fact in vision research that the HVS is efficient in analyzing moving luminance patterns. Therefore, luminance stimuli are the "golden standard" in all previously mentioned psychophysical studies. Luminance contrast is not only useful for motion perception, but in many other perceptual tasks; for example, high levels of spatial detail are best displayed by a luminance-based color map [69].

Unfortunately, pure luminance patterns cannot always be used. For example, the visualization of multivariate data often relies on a mapping to several color channels. We have to consider the limited budget of color dimensions to find an optimal choice of colors. If the data dimension associated with motion is less important than another data dimension, luminance contrast will be mapped to the latter dimension, while the moving pattern will be rather realized by color contrast.

In the previously mentioned psychophysical literature, motion discrimination is degraded only for very special conditions. M/D ratios are almost always close to one, except for nearly perfect isoluminant stimuli; e.g., Palmer et al. [62] report that already a one-percent luminance mismatch is sufficient to restore M/D ratios to one. Moreover, there is extensive evidence that suprathreshold chromatic contrasts promote the perception of motion for a variety of tasks and scenarios [14, 15, 16, 19, 73]. These investigations show that direction discrimination is possible for isoluminant patterns. Even though different tests lead to different M/D ratios, suprathreshold contrast generally supports motion detection. These psychophysical results are compatible with neurophysiological experiments in which color contrast is shown to support the perception of apparent motion by rhesus monkeys [21]. Some psychophysical experiments [56] even indicate that the M/D ratio is close to one in any case. As a common finding, we can state the following guideline for non-luminance patterns:

[G2] High chromatic contrasts support the discrimination of the direction of motion for (nearly) isoluminant patterns.

In this context, we would like to point out that perfect isoluminance is extremely difficult to achieve for practical visualization applications, which further supports the use of colored objects. First, typical computer-generated images simultaneously cover a range of different spatial frequencies: Edges contribute high spatial frequencies, whereas larger, interior parts result in low frequencies. Since isoluminance is affected by spatial frequency [1], a single, overall isoluminance point is hard to find. Second, isoluminance also depends on temporal frequency [53, 74]; and there is some indication for dynamic luminance artifacts from moving chromatic stimuli [57, 90].

Since, in general, motion strongly attracts visual attention [88], the recognition of motion is an important feature to steer the user's attention. Furthermore, the results from [22] indicate that motion can serve as a feature mask and lead to a selective filtering of objects, which is the basis for visual grouping. There is some indication that chromatic stimuli contribute to a salience map and that the analysis of their motion is directly computed from this map [47, 49]. Therefore, we propose:

[G3] Highlighting and visual grouping can be based on the motion of color patterns.

Motion discrimination has to be distinguished from the perception of smooth motion [56] and the speed of motion. There is psychophysical evidence that the perceived speed of a stimulus with fixed luminance contrast is strongly affected by changing the chromatic contrast. In experiments with moving sinusoidal gratings, the luminance mechanism is "diluted" by chromatic contrast [11, 12]. From a naive point of view, this dilution is surprising because, in stationary displays, redundant color scales, in which two or more channels are varied together, reinforce a signal. In contrast to the results for moving sinusoidal gratings, experiments with another, largely different set of stimuli and user tasks indicate that performance of observers can sometimes be improved by combining luminance and chromatic motion (both compared to stimuli that are only matching in luminance or color) [63]. In conclusion, the existence of possible interference problems leads to the following guideline:

[G4] Take into account that chromatic and achromatic channels can influence each other, especially for the perception of apparent speed.

Accordingly, this guideline proposes a restriction to variations in only a single color channel, which is compatible with some other rules for constructing effective color tables [67, 68]. Often, only a single color-model component is varied for univariate data. For example, luminance can be held constant to minimize interpretive errors caused by perceptual effects such as simultaneous contrast [82].

Considering *[G4]* and the previously mentioned investigations [12, 14, 56, 61], there is evidence for an influence of luminance and/or chromaticity contrasts on the perception of motion. Since this effect is particularly important for the perception of apparent speed, we propose this last rule:

[G5] Calibration is needed to represent ordinal data by the perceived speeds of colored patterns.

Note that *[G4]* and *[G5]* apply even when significant luminance contrasts are present in a color display.

5 Calibration

Two calibration procedures are required to implement guidelines *[G4]* and *[G5]*: the determination of isoluminance and a measurement of apparent speed.

Let us begin with the calibration of isoluminance. Different interpretations of isoluminance have to be distinguished. First, luminance could be equated according to the luminous efficiency function V_λ of the CIE standard observer [36]. Second, isoluminance can be determined from psychophysical experiments with the individual user. We choose the second approach because isoluminance settings can vary markedly among individuals [20]. The calibration is performed with the same viewing conditions under which the actual application will be run. In this way, additional parameters that influence the isoluminant point are taken into account, e.g., different color reproduction by different monitors and graphics cards, the adaptation to the environment, or the effect of the distance between user and screen. The minimum-motion method [1, 48] or the minimization of apparent flicker for a flickering stimulus [5] are often used in psychophysical experiments. To avoid the sometimes annoying flickering, we apply an alternative approach by Kindlmann et al. [40], which relies on the brain's ability to distinguish human faces. Their method is easy to use, comfortable, fast, and allows the user to match the luminance of color stimuli and determine the monitor's gamma. An implementation can be downloaded from their web page [39].

This calibration method is acceptable for practical applications because we do not have to achieve perfect isoluminance with respect to motion (as it is required for psychophysical experiments). In fact, many different parameters (such as spatial and temporal frequencies of the stimuli, or parafoveal vs. peripheral areas of the retina) have subtle effects on the isoluminance point and, therefore, it is dubious whether a perfect calibration can be achieved for animated computer-generated images.

The goal of the second, subsequent calibration procedure is to determine the apparent speed of stimuli that differ in luminance and/or color. We adopt the principal setup used by Cavanagh et

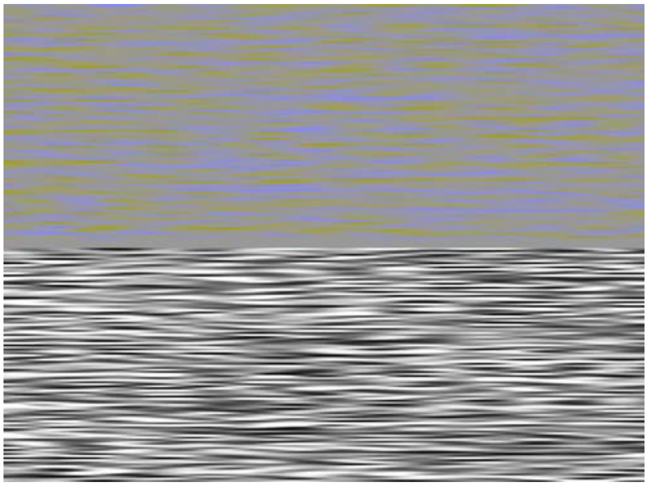


Figure 1: Calibration of perceived speeds. Two texture stimuli are rendered: A benchmark luminance contrast in the lower half of the screen and, in the upper half of the screen, a texture with the stimulus whose apparent speed has to be calibrated. The speed of both textures has to be matched by the user.

al. [12]. Figure 1 shows a typical screen configuration of the calibration system. Two horizontally drifting textures are used as stimuli. An achromatic luminance texture is presented in the lower half of the screen, serving as a benchmark for perceived speed. The color stimulus is rendered in the upper half of the screen. The two textures move in opposite directions to avoid any apparent cue for matching the speeds. Both textures are separated by a small, horizontal, and achromatic strip that has the mean luminance of the two stimuli. During the calibration task, the human observer has to match the perceived speeds of the two textures. The velocity, spatial structure, and contrast of the benchmark achromatic texture is determined by user-specified parameters and fixed during the calibration process to rule out side effects. (Even achromatic gratings exhibit some non-constant perceived speed; high spatial frequency and low contrast gratings appear to move slower [9, 76].) The speed of the color texture can be adjusted by the observer. To prevent the potential buildup of motion aftereffect, the user can reverse the directions of drift at any time by pressing a keyboard button.

The calibration is carried out for a few user-specified "key" stimuli that should represent the range of possible contrasts in the actual application. If needed, perceived speeds for intermediate contrasts are computed by interpolating between the "key" points. The corresponding interpolation of colors takes into account the monitor's gamma. In contrast to [12], we do not necessarily use sinusoidal gratings as drifting textures, but rather model the textures according to the targeted application. This approach has two advantages. First, the stimuli represent the needs of the actual application. Second, we avoid monotonous gratings that can be disturbing for the user, especially if the matching process takes some time. In the example of Figure 1, the moving stimuli are generated by a GPU-based implementation [86] of Line Integral Convolution (LIC) [8].

The speed calibration process was tested by an informal user study with computer science students (six males and one female) from our university. All users had normal or corrected-to-normal vision. After an introduction to the calibration system and a trial phase to become familiar with the system, the users were asked to match the stimulus shown in Figure 1. All tests were performed under rather typical viewing conditions (desktop environment with dim surrounding light, 21 inch iiyama CRT monitor, approximately 18 inch distance between eye and screen, ATI Radeon 9800XT graphics board, gamma $\gamma = 2.3$, Windows XP operating system without a built-in gamma correction). The calibration times for one stimulus varied between half a minute and three minutes. The relative (physical) speed of the YB stimulus and the achromatic stimulus of the same perceived speed was in the range between 1 and 1.5 (for the different observers). Some participants of the study reversed the directions of drift frequently while others did not use the reversal function at all. None of the users experienced a disturbing motion aftereffect or complained about other unpleasant visual effects of the moving textures.

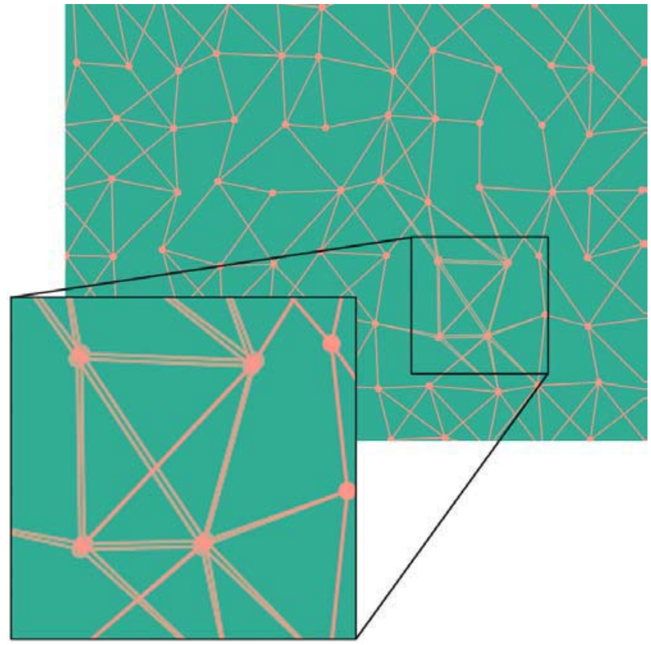


Figure 2: Grouping through motion in graph visualization. A subset of four nodes moves coherently. This motion is illustrated by a duplication and slight shift of the moving edges and points. A zoomed-in view of this region of interest is shown in the bottom-left part of the image.

6 Applications

6.1 Information Visualization

An important field in information visualization is concerned with the visual representation of multivariate data or complex interrelations between elements, e.g., in graphs or large tree hierarchies. Motion provides further useful perceptual dimensions in addition to color or shape [43]. Therefore, motion plays an important role in conveying additional data dimensions in the representation of multivariate data. Taking into account guidelines *[G2]* and *[G3]*, motion can be combined with color or other perceptual channels to extend the visualization space. Moreover, the preattentive [77] character of motion allows simple motion to effectively pop out objects in a crowded display which are dissimilar in all except their motion parameters [22, 60]. Therefore, motion can be used for filtering and brushing techniques [2, 3]. Brushing [4] highlights a subset of data interactively and thus allows the user to link related elements. Since this approach needs its own coding dimension, guidelines *[G2]* and *[G3]* relax the restriction to specific choices of colors and extend the range of possible combinations with other display dimensions.

Figure 2 illustrates the grouping behavior within the visualization of a graph. Four of the nodes move coherently (cf. the accompanying video on the project web page [85]) and show a strong

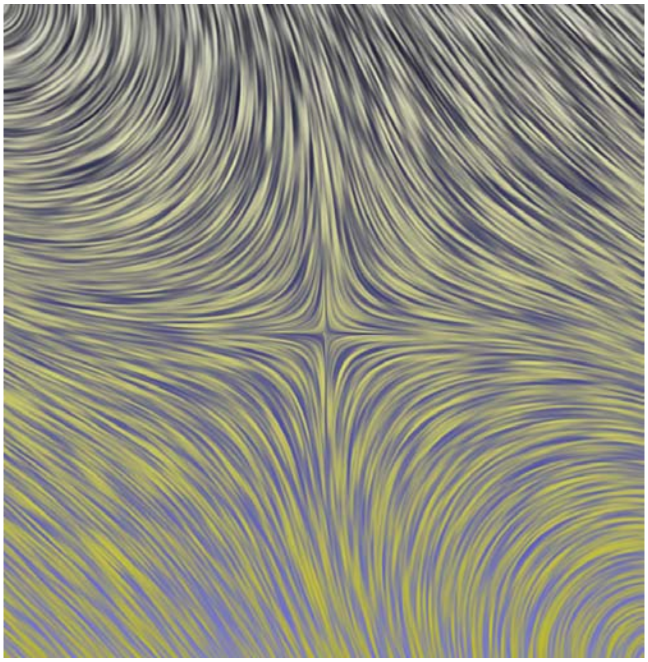


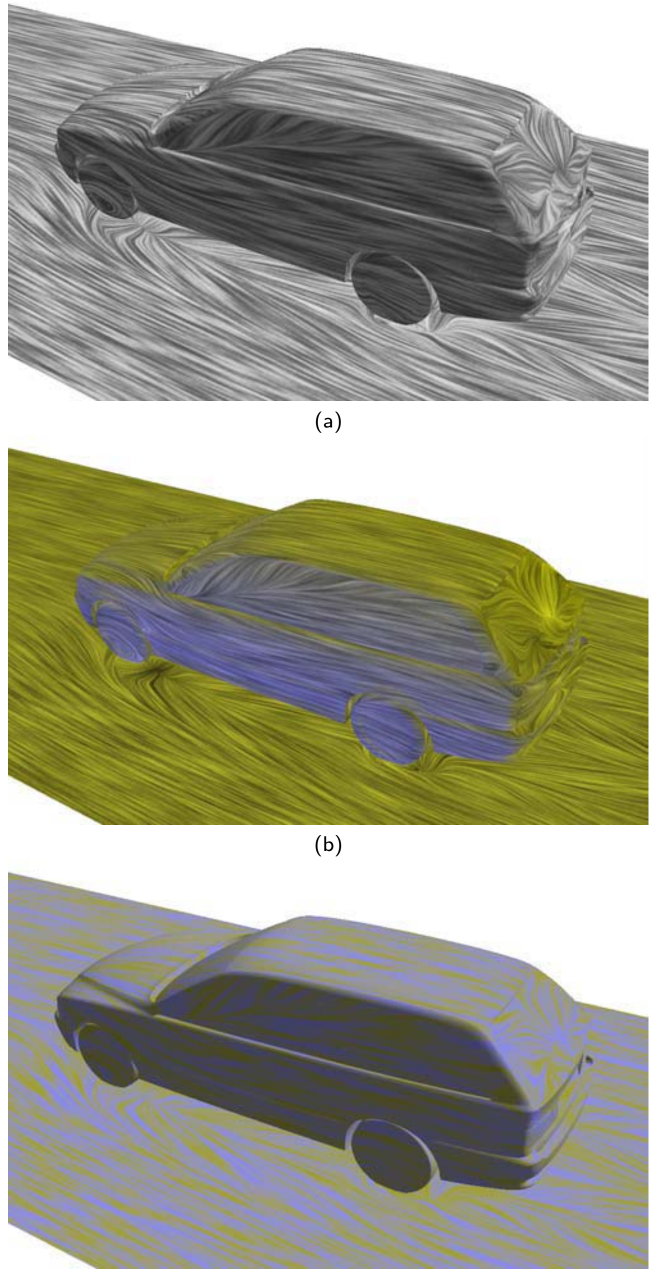
Figure 3: LIC visualization of a 2D vector field. An additional data dimension is represented by color coding. The lower part contains a nearly isoluminant YB contrast, which appears to move slower than the luminance patterns in the upper part (shown in the accompanying video [85]).

grouping property—they pop out as a connected element within the visualization. Background and foreground colors are chosen isoluminant. Here, the luminance calibration was performed by the author under the same viewing conditions as described in Section 5. The same viewing conditions are also assumed for the following example applications. This extreme example of Figure 2 demonstrates that even isoluminant colors are capable of supporting effective motion perception. Another effect that is not connected to motion perception should be noted here: The acuity limit for high spatial frequencies, as displayed in this example, is reduced at isoluminance (even in a steady image) [54].

6.2 Texture-Based Flow Visualization

One popular way of visualizing vector fields is based on dense texture representations (see [41, 72] for an overview), the role model of which is LIC [8]. In a standstill visualization, LIC shows only the orientation of the vector field, but not its direction. This problem can be overcome by displaying the direction of motion in an animation. The animation can be computed by employing a periodic filter kernel, where the phase of the filter is changed according to time [8]. Additional information—such as pressure or temperature of an underlying flow field—is often coded by means of a univariate color table. Figure 3 shows an example of a combined visualization of a vector field and one additional data dimension (the implementation is based on [86]). In sophisticated color-coding schemes, even more than a single data dimension can be taken into account [80].

As soon as color and animation are applied together, perception issues may arise. Considering guideline *[G5]*, a calibration of perceived speed is generally needed to faithfully represent the speed of moving patterns. The accompanying video [85] shows animated versions of Figure 3. The first sequence illustrates the animation with the same physical speed of LIC structures in all image regions.



(a)

(b)

(c)

Figure 4: Surface flow visualization: (a) shape and flow structures are represented by luminance contrasts; (b) cool/warm shading for the surface and luminance contrasts for LIC patterns; (c) shape is represented by luminance, flow structures by isoluminant YB contrast.

Due to the influence of different colors, some regions appear to move more slowly than others. The second sequence demonstrates that a correction of physical speed according to the calibration from Section 5 leads to a constant apparent speed. Here, the animation speed for the LIC computation is space-variant and takes into account the calibration data.

Figure 4 shows the visualization of the vector field from a CFD simulation of wind flow around an automobile. Details of the real-time implementation of flow visualization on surfaces are described in [87]. Here, additional perception issues become relevant because the shape of the surface has to be conveyed. One problem is that both shape and motion are best visualized by luminance contrasts. Different principal ways of simultaneously representing shape and vector field are possible. First, both shape and vector field could be mapped to the luminance channel, for example, by multiplying both contributions. This approach is illustrated in Figure 4 (a). A drawback is that the partly different needs of shape and vector field visualization interfere; for example, the left side of the car is only dimly illuminated and therefore the contrast is insufficient for the LIC structures. This observation leads to another approach in which the vector field is represented by luminance contrasts and shape by color contrasts (Figure 4 (b)). We adopt cool/warm shading [29] for the surface, with isoluminant cool/warm colors. According to guideline *[G4]*, the LIC texture is represented by luminance contrasts without any chromatic contrast. This approach gives a good visualization of motion *[G1]*, but a less distinct visualization of shape. Finally, the roles of luminance and chromaticity can be exchanged, as demonstrated in Figure 4 (c). Here, shape impression is predominant, at the cost of degraded motion perception. An advantage is that the LIC patterns do not stimulate an apparent, usually undesirable depth impression that is present in typical luminance-based LIC animations. Once again, perceived speed can be controlled by calibration *[G5]*.

6.3 Other Potential Applications

The guidelines could also influence other visualization and rendering techniques. One example could be kinetic shape visualization. Structure-from-motion perception [81] can be exploited to improve the recognition of shape. For example, structure-from-motion can be induced by a movement of points [78], which is used in kinetic visualization [51]. Additional information can be coded by colors. Lum et al. [51] apply cool/warm variations for shading and reserve luminance variations for outlines and highlights. The guidelines from Section 4 allow us to choose appropriate colors that support a good perception of motion. For example, high chromaticity contrasts should be applied and luminance and chromaticity channels could be separated.

As another example, efficient rendering of dynamic scenes could benefit from a sophisticated treatment of color and motion. In particular, there is a potential for improving saliency-oriented rendering frameworks [23, 89]. While the motion computation is often based on the luminance channel only (e.g., for the image-space velocity map in [89]), the motion map could take into account both luminance and chromatic channels in a more sophisticated approach. If chromatic and luminance inputs are treated equally, no further changes are required for the actual rendering framework and an extension to moving color attractors could readily be included. A more advanced approach, however, would require an extension of the visual attention model to incorporate color.

7 Conclusion and Future Work

The main goal of this paper has been to stimulate a better awareness for the opportunities and problems involved with the perception of moving color stimuli. Although luminance contrast plays a predominant role in motion perception, the effects of chromatic contrasts should not be underestimated. First, even the motion of purely chromatic stimuli can be discriminated, which allows us to "stretch" the available design space for animated visualizations. Second, luminance stimuli can be affected by chromatic contrast. For example, adding chromatic contrast to a luminance stimulus may degrade the perceived velocity, i.e., the design space is restricted in this case. Based on psychophysical evidence, some guidelines have been proposed for color design in visualization applications, along with a practical calibration process. Finally, a few applications have been discussed. We think, however, that a differentiated view on motion and color could have an even wider impact on numerous other applications in visualization and computer graphics.

In future work, user studies could be conducted to test the proposed guidelines for various application scenarios. It would also be interesting to evaluate the calibration process in more detail by statistically significant user tests. Another line of future research could address specific combinations of chromatic motion and further perceptual features like texture.

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