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 practical calibration procedure that improves the reliability of motion representation. The usefulness of the guidelines is demonstrated for a number of applications such as texture-based flow visualization, graph and tree visualization, and kinetic 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* [82], 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 [83]. 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 goal is to stimulate an increased awareness for both the opportunities and issues involved in the design of colored animations.

The contributions of this paper are: First, relevant findings 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 practical guidelines for the design of animated graphics. Third, it is shown that a calibration is required for some applications and a practical calibration procedure is suggested to realize such systems in a real-world work environment. Fourth, a number of typical applications are discussed to demonstrate how the guidelines and the calibration approach can be used for effective visualizations.

2 PREVIOUS WORK

Various aspects of human visual perception are presented in a number of SIGGRAPH courses [13, 25, 28, 35, 74], IEEE Visualization tutorials [27, 42], and in a book by Ware [82].

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 [32, 33] 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 patterns and 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 [26, 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 [69]. The spatiotemporal CSF [39] describes the detectability of moving patterns and is an important element in motion-aware metrics [58, 59]. Saliency models [36] simulate where people focus their attention in images to improve the efficiency of rendering [6, 24]. Of particular interest are models that take into account motion as part of the saliency computation [7, 87].

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3 PSYCHOPHYSICAL AND PHYSIOLOGICAL RESEARCH

We briefly discuss some aspects of color vision and motion detection within the HVS. Detailed background information on neuroscience and human vision can be found in [34, 38]. Two categories of photoreceptors in the retina serve as detectors for light that is collected by the eye: rods and cones. Cones dominate the initial response at normal light levels and 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, 89], 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, 31, 44, 46, 56, 61, 78].

On the other hand, the loss of motion perception in color vision is not complete, especially for suprathreshold stimuli. Both the direction of motion of drifting sinewave gratings and the frequency of flicker can be discriminated at contrasts close to, although not at, detection threshold [10, 20, 29, 56, 62]. Cropper [14] reports that, for suprathreshold chromatic contrast, both discrimination of direction of motion 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 [72]. 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, 19, 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, 70].

In addition to the detection of direction of motion, the perceived magnitude of the velocity 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, 31, 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 [75]).

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 abberation) is extremely unlikely [31, 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, 88]. 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. 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. [38]).

4 DESIGN GUIDELINES

We try to adapt the above psychophysical findings for the needs of practical 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 facilitate the design of effective and efficient rendering techniques, we combine and interpret the results of the aforementioned literature to propose some practical guidelines. The main goal is to stimulate an awareness for both the opportunities and limitations associated with moving color patterns. In accordance with a prevalent assessment in the visualization community, the prime directive 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 perceptional tasks; for example, high levels of spatial detail are best displayed by a luminance-based color map [68].

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 1. Moreover, there is extensive evidence that suprathreshold chromatic contrasts promote the perception of motion for a variety of tasks and scenarios [14, 15, 16, 20, 72]. 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 [22]. 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 first 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, 73]; and there is some indication for dynamic luminance artifacts from moving chromatic stimuli [57, 88].

Since, in general, motion strongly attracts visual attention [86], the recognition of motion is an important feature to steer the user's attention. Furthermore, the results from [23] 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]. From the above psychophysical results we conclude:

[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 [66, 67]. 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 [81].

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 on 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

To realize guidelines *[G4]* and *[G5]*, two calibration procedures are required: 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 [37]. 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 [21]. 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. [41], 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 [40].

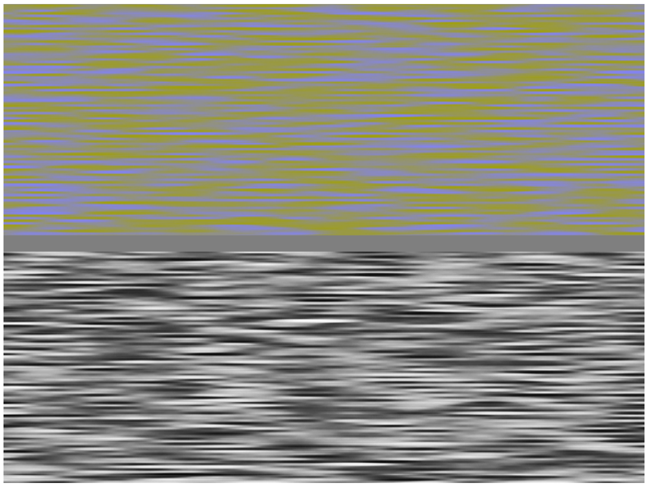


Figure 1: Calibration of perceived speeds. Two texture stimuli are rendered: A benchmark luminance contrast in the lower half of the screen and a chromatic contrast texture in the upper half of the screen. The speed of both textures has to be matched by the user.

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 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 minimize cues for tracking eye motion and 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, 75].) The speed of the color texture can be adjusted by the observer. To prevent the annoying buildup of motion aftereffect, the directions of drift can be reversed 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 very well. Second, we avoid monotonous gratings that can be quite annoying and 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 [84] of Line Integral Convolution (LIC) [8].

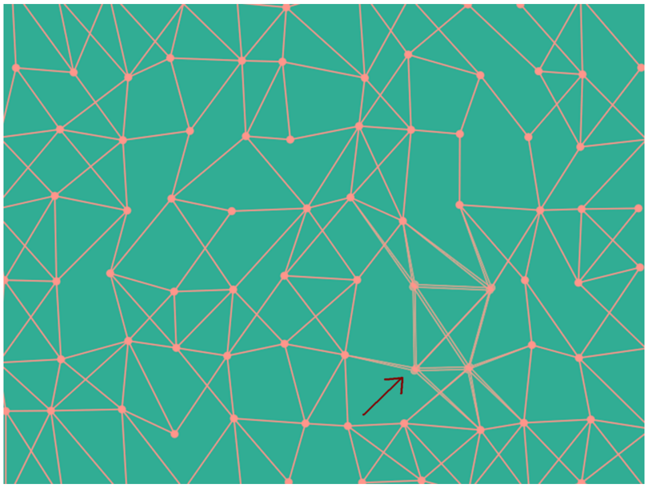


Figure 2: Grouping through motion in graph visualization. A subset of four nodes moves coherently. This motion is illustrated by a duplication and slight shift of the moving edges and points (in the region above, and to the right of, the dark arrow).

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 [76] character of motion allows simple motion to effectively pop-out objects in a crowded display which are dissimilar in all except their motion parameters [23, 60]. Therefore, motion can be used for filtering and brushing techniques [2, 3]. Brushing [4] highlights a subset of the 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) and show a strong grouping property—they pop-out as a connected element within the visualization. Background and foreground colors are chosen isoluminant. The luminance calibration (Section 5) was performed by the author 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 $\gamma = 2.2$, Windows XP operating system without a built-in gamma correction). The same viewing conditions are assumed for the following example applications as well. This extreme example of Fig-

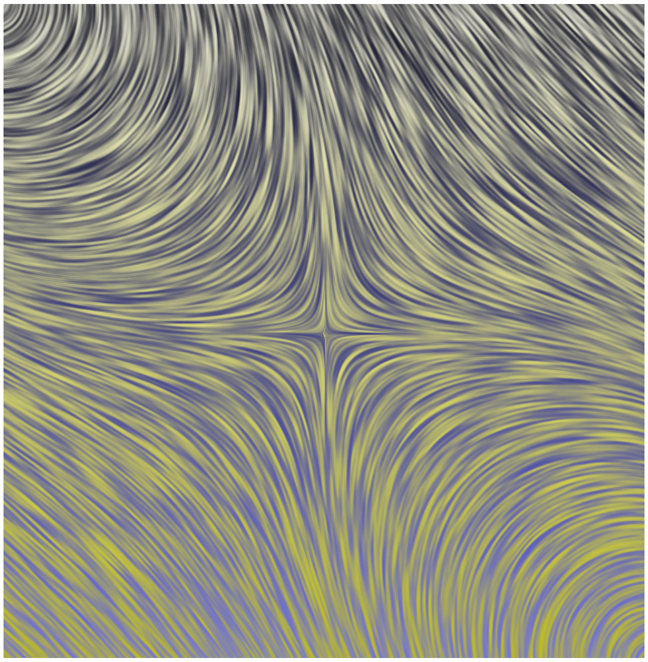


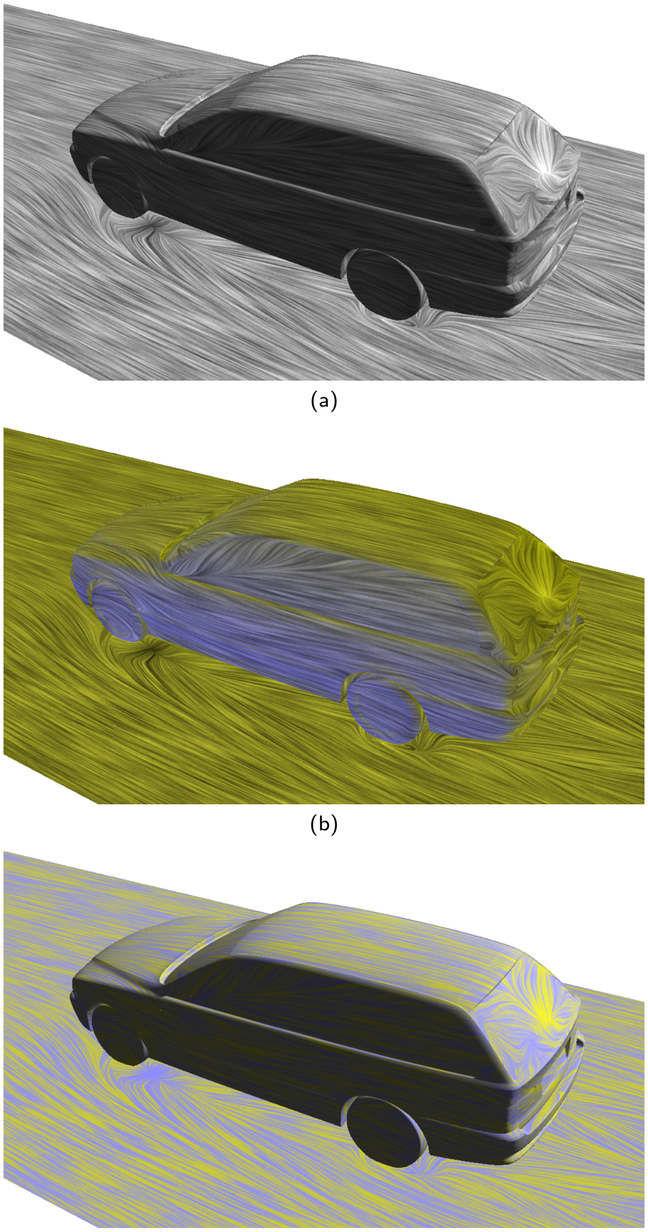
Figure 3: LIC visualization of a 2D vector field. An additional data dimension is represented by color coding. The lower part contains an isoluminant YB contrast, which appears to move slower than the luminance patterns in the upper part (shown in the accompanying video).

ure 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 [71] 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 [84]). In sophisticated color-coding schemes, even more than a single data dimension can be taken into account [79].

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 shows animated versions of Figure 3. The first sequence illustrates the animation with the same physical speed of LIC structures in all image regions. 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 speeds 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.



(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.

Figure 4 shows the visualization of the vector field from a CFD simulation of wind flow around an automobile. Details of the realtime implementation of flow visualization on surfaces are described in [85]. 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. Three 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 [30] 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 Kinetic Shape Visualization

Structure-from-motion perception [80] can be exploited to improve the recognition of shape. For example, structure-from-motion can be induced by a movement of points [77], 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.

6.4 Other Potential Applications

The guidelines could also influence other visualization and rendering techniques. One example could be video visualization [18], which plays an important role by providing tools that allow security personnel to quickly scan films for conspicuous contents in data from video surveillance systems. Usually, surveillance cameras record single-channel data (grayscale images in the visible or infrared range) that can be displayed by univariate color tables for highlighting interesting details. The guidelines of this paper could support the design of these color tables: Details can be emphasized in both standstill images and animations (e.g., by high luminance contrasts), while the background is still displayed as surrounding context, but less prominently and with lower apparent speed (e.g, by little luminance contrast).

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 [24, 87] because motion (even purely chromatic) can draw the viewer's attention [47]. However, the motion computation is often based on the luminance channel only (e.g., for the velocity map in image space [87]). In fact, the motion map should take into account both luminance and chromatic channels. 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 sophisticated approach, however, would require an extension of the visual attention model to incorporate color.

7 CONCLUSION

The main goal of this paper is 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 constricted 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 that benefit from these guidelines 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.

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REFERENCES

[1] S. M. Anstis and P. Cavanagh. A minimum motion technique for judging equiluminance. In J. D. Mollon and E. T. Sharpe, editors, *Colour Vision*, pages 155–166, New York, 1983. Academic Press.

[2] L. Bartram. Perceptual and interpretative properties of motion for information visualization. Technical Report CMPT-TR-1997-15, School of Computing Science, Simon Fraser University, 1997.

[3] L. Bartram and C. Ware. Filtering and brushing with motion. *Information Visualization*, 1(1):66–79, 2002.

[4] R. A. Becker and W. S. Cleveland. Brushing scatterplots. *Technometrics*, 29(2):127–142, 1987.

[5] R. M. Boynton. *Human Color Vision*. Holt, Rinehart & Winston, New York, 1979.

[6] R. Brown, B. Pham, and A. Maeder. A fuzzy model for scene decomposition based on preattentive visual features. In *Proceedings of SPIE, 3644*, pages 461–472, 1999.

[7] R. Brown, B. Pham, and A. Maeder. Visual importance-biased image synthesis animation. In *Proceedings of the 1st International Conference on Computer Graphics and Interactive Techniques in Australasia and South East Asia*, pages 63–70, 2003.

[8] B. Cabral and L. C. Leedom. Imaging vector fields using line integral convolution. In *Proceedings of SIGGRAPH 1993*, pages 263–272, 1993.

[9] F. W. Campbell and L. Maffei. The influence of spatial frequency and contrast on the perception of moving patterns. *Vision Research*, 21:713–721, 1981.

[10] P. Cavanagh and S. Anstis. The contribution of color to motion in normal and color-deficient observers. *Vision Research*, 31:2109–2148, 1991.

[11] P. Cavanagh and O. E. Favreau. Color and luminance share a common motion pathway. *Vision Research*, 25:1595–1601, 1985.

[12] P. Cavanagh, C. W. Tyler, and O. E. Favreau. Perceived velocity of moving chromatic gratings. *Journal of the Optical Society of America A*, 1(8):893–899, 1984.

[13] A. Chalmers, S. Daly, A. McNamara, K. Myszkowski, H. Rushmeier, and T. Troscianko. Seeing is believing: Reality perception in modeling, rendering and animation. *SIGGRAPH 2001 Course #21 Notes*, 2001.

[14] S. J. Cropper. Velocity discrimination in chromatic gratings and beats. *Vision Research*, 34:41–48, 1994.

[15] S. J. Cropper and A. M. Derrington. Motion of chromatic stimuli: First-order or second-order? *Vision Research*, 34:49–58, 1994.

[16] S. J. Cropper and A. M. Derrington. Rapid colour-specific detection of motion in human vision. *Nature*, 379:72–74, 1996.

[17] S. Daly. The visible differences predictor: An algorithm for the assessment of image fidelity. In A. B. Watson, editor, *Digital Images and Human Vision*, pages 179–206, Cambridge, 1993. MIT Press.

[18] G. Daniel and M. Chen. Video visualization. In *IEEE Visualization 2003 Conference*, pages 409–416, 2003.

[19] A. M. Derrington and D. R. Badcock. The low level motion system has both chromatic and luminance inputs. *Vision Research*, 25:1879–1884, 1985.

[20] A. M. Derrington and G. Henning. Detecting and discriminating the direction of motion of luminance and colour gratings. *Vision Research*, 33:799–811, 1993.

[21] H. L. DeVries. The heredity of the relative numbers of red and green receptors in the human eye. *Genetica*, 24:199–212, 1948.

[22] K. R. Dobkins and T. D. Albright. What happens if it changes color when it moves?: The nature of chromatic input to macaque visual area MT. *Journal of Neuroscience*, 14:4854–4870, 1994.

[23] J. Driver, P. McLeod, and Z. Dienes. Motion coherence and conjunction search: Implications for guided search theory. *Perception and Psychophysics*, 51(1):79–85, 1992.

[24] R. Dumont, F. Pellacini, and J. A. Ferwerda. Perceptually-driven decision theory for interactive realistic rendering. *ACM Transactions on Graphics*, 22(2):152–181, 2003.

[25] F. Durand, M. Agrawala, B. Gooch, V. Interrante, V. Ostromoukhov, and D. Zorin. Perceptual and artistic principles for effective computer depiction. *SIGGRAPH 2002 Course #13 Notes*, 2002.

[26] J. Ferwerda, S. N. Pattanaik, P. Shirley, and D. P. Greenberg. A model of visual adaptation for realistic image synthesis. In *Proceedings of SIGGRAPH 1996*, pages 249–258, 1996.

[27] J. A. Ferwerda, H. Rushmeier, and B. Watson. Psychometrics 101: How to design, conduct, and analyze perceptual studies of computer graphics visualization techniques. *IEEE Visualization 2002 Tutorial #7*, 2002.

[28] J. A. Ferwerda, H. Rushmeier, and B. Watson. Frontiers in perceptually-based image synthesis: Modeling, rendering, display, validation. *SIGGRAPH 2003 Course #3 Notes*, 2003.

[29] K. R. Gegenfurtner and M. J. Hawken. Temporal and chromatic properties of motion mechanisms. *Vision Research*, 35:1547–1563, 1995.

[30] A. Gooch, B. Gooch, P. Shirley, and E. Cohen. A non-photorealistic lighting model for automatic technical illustration. In *SIGGRAPH 1998 Conference Proceedings*, pages 101–108, 1998.

[31] M. J. Hawken, K. R. Gegenfurtner, and C. Tang. Contrast dependence of colour and luminance motion mechanisms in human vision. *Nature*, 367:268–270, 1994.

[32] C. G. Healey, K. S. Booth, and J. T. Enns. Visualizing real-time multivariate data using preattentive processing. *ACM Transactions on Modeling and Computer Simulation*, 5(3):190–221, 1995.

[33] C. G. Healey, K. S. Booth, and J. T. Enns. High-speed visual estimation using preattentive processing. *ACM Transactions on Computer-Human Interaction*, 3(2):107–135, 1996.

[34] L. M. Hurvich. *Color Vision*. Sinauer Associates, Sunderland, 1981.

[35] V. Interrante, P. Rheingans, J. Ferwerda, R. Gossweiler, and C. Healey. Applications of visual perception in computer graphics. *SIGGRAPH 1998 Course #32 Notes*, 1998.

[36] L. Itti and C. Koch. Computational modelling of visual attention. *Nature Reviews Neuroscience*, 2(3):194–203, 2001.

[37] D. B. Judd. Report of U.S. Secretariate Committee on Colorimetry and Artificial Daylight. In *CIE Proceedings*. Bureau Central CIE, Paris, 1951.

[38] E. R. Kandel, J. H. Schwartz, and T. M. Jessell, editors. *Essentials of Neural Science and Behavior*. Appleton & Lange, Norwalk, 1995.

[39] D. H. Kelly. Motion and vision. II. Stabilized spatio-temporal threshold surface. *Journal of the Optical Society of America*, 69(10):1340–1349, 1979.

[40] G. Kindlmann. Face-based luminance matching: Software. Web page: http://www.cs.utah.edu/~gk/lumFace, 2002.

[41] G. Kindlmann, E. Reinhard, and S. Creem. Face-based luminance matching for perceptual colormap generation. In *IEEE Visualization 2002 Conference*, pages 299–306, 2002.

[42] H. Levkowitz, V. Interrante, and H. P. Meinzer. Perception for visualization: From design to evaluation. *IEEE Visualization 1998 Tutorial #4*, 1998.

[43] S. Limoges, C. Ware, and W. Knight. Displaying correlations using position, motion, point size or point color. In *Graphics Interface*, pages 262–265, 1989.

[44] M. Livingstone and D. Hubel. Psychophysical evidence for separate channels for the perception of form, color, movement, and depth. *Journal of Neuroscience*, 7:3416–346, 1987.

[45] N. K. Logothetis, P. H. Schiller, E. Charles, and A. C. Hurlbert. Perceptual deficits and the activity of the color-opponent and broad-band pathways at isoluminance. *Science*, 247(4939):214–217, 1990.

[46] Z.-L. Lu, L. Lesmes, and G. Sperling. Perceptual motion standstill from rapidly moving chromatic displays. In *Proceedings of National Academy of Science, 96*, pages 15374–15379, 1999.

[47] Z.-L. Lu and G. Sperling. Attention-generated apparent motion. *Nature*, 379:237–239, 1995.

[48] Z.-L. Lu and G. Sperling. Sensitive calibration and measurement procedures based on the amplification principle in motion perception. *Vision Research*, 41(18):2355–2374, 2001.

[49] Z.-L. Lu and G. Sperling. Three-systems theory of human visual motion perception: Review and update. *Journal of the Optical Society of America A*, 18(9):2331–2370, 2001.

[50] J. Lubin. A visual system discrimination model for imaging system design and evaluation. In E. Peli, editor, *Visual Models for Target Detection and Recognition*, pages 245–283, New York, 1995. World Scientific.

[51] E. B. Lum, A. Stompel, and K.-L. Ma. Using motion to illustrate static 3D shape—kinetic visualization. *IEEE Transactions on Visualization and Computer Graphics*, 9(2):115–126, 2003.

[52] A. McNamara, A. G. Chalmers, T. Troscianko, and I. Gilchrist. Comparing real and synthetic scenes using human judgements of lightness. In *Eurographics Workshop on Rendering*, pages 207–219, 2000.

[53] A. B. Metha and K. T. Mullen. Failure of direction discrimination at detection threshold for both fast and slow chromatic motion. *Journal of the Optical Society of America A*, 15(12):2945–2950, 1998.

[54] K. T. Mullen. The contrast sensitivity of human colour vision to red–green and blue–yellow chromatic gratings. *The Journal of Physiology*, 359(1):381–400, 1985.

[55] K. T. Mullen and C. L. Baker, Jr. A motion aftereffect from an isoluminant stimulus. *Vision Research*, 25:685–688, 1985.

[56] K. T. Mullen and J. C. Boulton. Absence of smooth motion perception in color vision. *Vision Research*, 32:483–488, 1992.

[57] K. T. Mullen, T. Yoshizawa, and C. L. Baker, Jr. Luminance mechanisms mediate the motion of red-green isoluminant gratings: The role of “temporal chromatic aberration”. *Vision Research*, 43(11):1235–1247, 2003.

[58] K. Myszkowski, P. Rokita, and T. Tawara. Perception-based fast rendering and antialiasing of walkthrough sequences. *IEEE Transactions on Visualization and Computer Graphics*, 6(4):360–379, 2000.

[59] K. Myszkowski, T. Tawara, H. Akamine, and H.-P. Seidel. Perception-guided global illumination solution for animation rendering. In *Proceedings of SIGGRAPH 2001*, pages 221–230, 2001.

[60] K. Nakayama and G. H. Silverman. Serial and parallel processing of visual feature conjunctions. *Nature*, 320:264–265, 1986.

[61] D. Nguyen-Tri and J. Faubert. Perceived speed of drifting chromatic gratings is mechanism dependent. *Vision Research*, 42(10):2073–2079, 2002.

[62] J. Palmer, L. A. Mobley, and D. Y. Teller. Motion at isoluminance: Discrimination/detection ratios and the summation of luminance and chromatic signals. *Journal of the Optical Society of America A*, 10:1353–1362, 1993.

[63] T. V. Papathomas, A. Gorea, and B. Julesz. Two carriers for motion perception: Color and luminance. *Vision Research*, 31:1883–1892, 1991.

[64] S. N. Pattanaik, J. A. Ferwerda, D. A. Greenberg, and M. D. Fairchild.

A multiscale model of adaptation and spatial vision for realistic imaging. In *Proceedings of SIGGRAPH 1998*, pages 287–298, 1998.

[65] V. S. Ramachandran and R. L. Gregory. Does colour provide an input to human motion perception? *Nature*, 275:55–57, 1978.

[66] P. Rheingans. Dynamic color mapping of bivariate qualitative data. In *IEEE Visualization 2002 Conference*, pages 159–166, 1997.

[67] P. Rheingans and C. Landreth. Perceptual principles for effective visualizations. In G. Grinstein and H. Levkowitz, editors, *Perceptual Issues in Visualization*, pages 59–74. Springer Verlag, 1995.

[68] B. Rogowitz and L. Treinish. How NOT to lie with visualization. *Computers in Physics*, 10(3):268–274, 1996.

[69] H. Rushmeier, G. J. Ward, C. Piatko, P. Sanders, and B. Rust. Comparing real and synthetic images: Some ideas about metrics. In *EG Rendering Workshop 1995*, pages 82–91, 1995.

[70] H. Saito, K. Tanaka, M. Yasuda, and A. Mikami. Directionally selective response of cells in the middle temporal area (MT) of the macaque monkey to the movement of equiluminous opponent color stimuli. *Brain Research*, 15:1–14, 1989.

[71] A. Sanna, B. Montrucchio, and P. Montuschi. A survey on visualization of vector fields by texture-based methods. *Recent Res. Devel. Pattern Rec.*, 1:13–27, 2000.

[72] A. E. Seiffert and P. Cavanagh. Position-based motion perception for colour and texture stimuli: Effects of contrast and speed. *Vision Research*, 39:4172–4185, 1999.

[73] C. F. Stromeyer, R. E. Kronauer, A. Ryu, A. Chaparro, and R. T. Eskew. Contributions of human long-wave and middle-wave cones to motion detection. *The Journal of Physiology*, 485(1):221–243, 1995.

[74] R. M. Taylor II, C. Ware, and V. Interrante. Perceptually-based visualization design. *SIGGRAPH 2003 Course #45 Notes*, 2003.

[75] P. Thompson. Perceived rate of movement depends on contrast. *Vision Research*, 22:377–380, 1982.

[76] A. Treisman. Preattentive processing in vision. *Computer Vision, Graphics, and Image Processing*, 31:156–177, 1985.

[77] S. Treue, M. Husain, and R. A. Andersen. Human perception of structure from motion. *Vision Research*, 31(1):59–75, 1991.

[78] T. Troscianko and M. Fahle. Why do isoluminant stimuli appear slower? *Journal of the Optical Society of America A*, 5(6):871–880, 1988.

[79] T. Urness, V. Interrante, I. Marusic, E. Longmire, and B. Ganapathisubramani. Effectively visualizing multi-valued flow data using color and texture. In *IEEE Visualization 2003 Conference*, pages 115–122, 2003.

[80] H. Wallach and D. N. O'Connell. The kinetic depth effect. *Journal of Experimental Psychology*, 45(4):205–217, 1953.

[81] C. Ware. Color sequences for univariate maps. *IEEE Computer Graphics and Applications*, 8(5):41–49, 1988.

[82] C. Ware. *Information Visualization: Perception for Design*. Morgan Kaufmann, San Francisco, 2000.

[83] C. Ware. Lecture 2: Early vision and color. In *SIGGRAPH 2003 Course #45 Notes*, 2003.

[84] D. Weiskopf, G. Erlebacher, and T. Ertl. A texture-based framework for spacetime-coherent visualization of time-dependent vector fields. In *IEEE Visualization 2003 Conference*, pages 107–114, 2003.

[85] D. Weiskopf and T. Ertl. A hybrid physical/device-space approach for spatio-temporally coherent interactive texture advection on curved surfaces. In *Graphics Interface 2004*, 2004.

[86] W. Wolfe. Visual search. In H. E. Pashler, editor, *Attention*, pages 13–73, Hove, 1998. Psychology Press.

[87] H. Yee, S. Pattanaik, and D. P. Greenberg. Spatiotemporal sensistivity and visual attention for efficient rendering of dynamic environments. *ACM Transactions on Graphics*, 20(1):39–65, 2001.

[88] T. Yoshizawa, K. T. Mullen, and C. L. Baker, Jr. Absence of a chromatic linear motion mechanism in human vision. *Vision Research*, 40:1993–2010, 2000.

[89] S. M. Zeki. Uniformity and diversity of structure and function in rhesus monkey prestriate visual cortex. *The Journal of Physiology*, 277:273–290, 1978.