Perceptions of Crosstalk and the Possibility of a Zoneless Autostereoscopic Display

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ABSTRACT

Overlaid stereo image pairs, viewed without stereo demultiplexing optics, are not always perceived as a ghosted image: if image generation and display parameters are adjusted so that disparities are small and limited to foreground and background regions, then the perception is rather more of blurring than of doubling. Since this blurring seems natural, comparable to the blurring due to depth-of-focus, it is unobjectionable. In contrast, the perception of ghosting seems always to be objectionable. Now consider the possibility that there is a perceptual regime in which disparity is small enough that perception of crosstalk is as blurring rather than as ghosting, but it is large enough to stimulate depth perception. If such a perceptual region exists, then it might be exploited to relax the strict “crosstalk minimization” requirement normally imposed in the engineering of stereoscopic displays. This paper reports experiments that indicate that such a perceptual region does actually exist. We suggest a stereoscopic display engineering design concept that illustrates how this observation might be exploited to create a zoneless autostereoscopic display. By way of introduction and motivation, we begin from the observation that, just as color can be shouted in primary tones or whispered in soft pastel hues, so stereo can be shoved in your face or raised ever so gently off the screen plane. We review the problems with "in your face stereo", we demonstrate that "just enough reality" is both gentle and effective in achieving stereoscopy's fundamental goal: resolving the front-back ambiguity inherent in 2D projections, and we show how this perspective leads naturally to the relaxation of the requirement for crosstalk reduction to be the main engineering constraint on the design of stereoscopic display systems.

1. INTRODUCTION

This work started with the conception and study of a "kinder gentler" approach to stereo, striving for "just enough reality" in contrast to trying to achieve precise "virtual reality". The approach uses optical and algorithmic image adjustments, along with the judicious application of established psychophysical principles, to achieve adequate stereo perception while minimizing eyestrain, fatigue, "virtual reality sickness", etc. In pursuing this goal it became apparent that overlaid stereo image pairs, viewed without stereo demultiplexing optics, are not always perceived as a "ghosted" (doubled) image. If the image generation and display parameters are adjusted so that disparities are small and essentially limited to foreground and background regions then the perception is rather more of blurring than of doubling; indeed once mentioned this seems obvious and trivial. Since foreground and background blurring is quite natural, e.g., when it is due to depth-of-focus, it is unobjectionable. In contrast, the perception of ghosting seems always to be objectionable. Now consider the case of a stereopair viewed via the usual demultiplexing optics, these optics being of real vs. ideal engineering, i.e., they allow some crosstalk between left and right eye image channels. This crosstalk is normally perceived as ghosting. But we may guess that in this case as well, if disparities are small and essentially limited to foreground and background regions then the crosstalk will be perceived not as ghosting but rather as foreground and background blur. This hypothesis was in fact confirmed by experiments with stereo display apparatus using shutter glasses whose performance can be degraded by adjusting the LCD shutter excitation voltages. Recent more detailed experiments using high quality shuttering but algorithmically blended left and right eye image pairs has quantitatively identified the region in the crosstalk-disparity plane in which disparity is at once large enough to stimulate stereopsis and small enough that crosstalk is perceived as blur rather

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than as ghosting. Using a matrix of image pairs generated with an object distance of about 30 cm, interocular separations at 1 mm intervals from 0 to 40 mm, "center-of-interest" compensation to confine perceived crosstalk to foreground and background regions, and systematically increasing crosstalk fractions, there is a bell-shaped region of stereo perception that peaks at an interocular separation of about 2.5 mm, at which point crosstalk can be as large as 0.40 (each eye seeing a blend of 60% of "its" image and 40% of "the other eye's" image) without destroying stereo perception and without stimulating the perception of ghosting. Having thus removed the requirement to minimize crosstalk from top place on the stereo display system designer's constraint list, it now becomes possible to think about the possible engineering and perceptual advantages of systems in which a substantial degree of crosstalk is allowed. One of these consequences appears to be the possibility of zoneless autostereoscopic displays using, e.g., electronically switched louver filters that generate a suitably non-lambertian screen luminance pattern.

For background, and to introduce the subject to the sophisticated but not necessarily presumed to be stereo-knowledgeable reader, the perception of depth in a nearby scene depends on about ten cues of which the strongest is binocular stereopsis, the image pair disparity due to the slightly different perspective that the two eyes have on the scene. Imagery rendered on a flat surface — paper, TV screen, etc. — can fool the eye-brain into seeing it in depth via some multiplexing trick that paints left and right eye images on the same screen but allows the left eye to see only the left eye's view and vice versa. Viewed without the corresponding demultiplexing hardware in place, both views are seen — flat of course — by both eyes, with corresponding scene points seen offset left-right on the screen in proportion to their actual offset front-back in the three dimensional scene. This left-right on-screen offset proportional to actual front-back offset we call "disparity" or "on-screen disparity". [2][3][7]

Another important cue to the frontness and backness in the scene is the eyes' focus or "accommodation". Except for scene objects that by chance happen to be at the screen distance, the accommodation is *always wrong*: the eyes have to focus on on-screen pixels, but the disparity tells the brain that the objects represented by those pixels are behind or in front of the screen. This "accommodation-convergence conflict", and other conflicts among depth cues, result in physiological and psychological stresses and reactions to those stresses that collectively we call "virtual reality sickness". This problem is the main topic of Section 2, *Just Enough Reality*. [5][6][9]

The new work reported in this paper began as an attempt to ameliorate virtual reality sickness by "softening" binocular stereopsis, minimizing its conflict with accommodation and other depth cues. It seemed also possible to strengthen depth perception by understanding and taking advantage of another ten or so visual illusions whereby a sense of depth is stimulated by suitably viewed flat images. The surprise was that extremely small interocular separations [1], only a few percent of the nominal 60-65 mm for human adults, produces on-screen disparities that are adequate to stimulate depth perception. This observation is the main topic of Section 3, *How Much is Just Enough?*

Something that fell out of this observation is that, when viewed without stereo demultiplexing hardware, these very small on-screen disparities are perceived not as ghosting but rather as blur. Since a small left-right image shift can make the on-screen disparity actually zero at the scene's center-of-interest, this blur can be made entirely unobjectionable by confining it to the scene background and foreground, which are normally blurred by the depth-of-focus effect anyway. In contrast, even small amounts of ghosting — due to imperfections in the stereo demultiplexing hardware — are extremely objectionable; indeed, minimizing ghosting is often the stereo display system design engineer's most frustrating challenge. This is the main topic of Section 4, *Perceptions of Crosstalk*.

While stereo demultiplexing hardware usually uses a light separation device — shutters or polarizers — at the eyes, there are "autostereoscopic" displays that use barrier masks or light-steering ("lenslet" or "lenticule") arrays to produce the stereo effect without eyewear. Their main disadvantage is that they render the left and right eye images appropriately visible and invisible only within particular angular zones; if the viewer's left eye is not located in a left-eye angular zone and his or her right eye is not at the same time located in a right-eye angular zone, then (a) stereo is not perceived, and (b) the confusion that is perceived is unpleasant. So it is a recognized engineering goal to achieve a *zoneless* autostereoscopic display. We have made some progress toward demonstrating that small on-screen disparities, center-of-interest compensation, and the resulting perception of crosstalk as unobjectionable blur vs. objectionable ghosting, might be exploited to achieve this goal. This progress is the main topic of Section 5, *Prospects of Zoneless Autostereoscopic Displays*.

Conclusions and an agenda for future work are discussed in Section 6.

2. "JUST ENOUGH REALITY" OR "KINDER GENTLER STEREO"

How to build a 3D-stereoscopic camera and display system that reproduces exactly — at least geometrically — the retinal images of the original scene has been understood since the early days of photography. Almost as old and well known are a host of heuristic rules for deviating from this perfect geometry for the sake of mitigating its negative side effects; mitigation is necessary, because the perceptual synthesis is perfect only in the domain of geometrical optics. The perceptual conflict between the geometrical cues that are synthesized correctly and other cues that are not synthesized correctly causes physiological and psychological stresses that have recently come to be known as "virtual reality sickness", "simulator sickness", etc. These conflicts are physically and mentally uncomfortable. And despite the availability — and the routine application — of nominally mitigating heuristics, we often notice that people to whom 3D-stereoscopic displays are easily available nevertheless avoid using them except when they are essential to performing some task, e.g., a delicate teleoperation.

These observations stimulate us to seek a "kinder gentler stereo": a natural approach to 3D-stereoscopic display that is as free of stress as is naked eye viewing of the real world. We seek an approach to stereo image-pair capture and generation without cue conflicts, without eyewear, without viewing zones, and with negligible "lock-in" time to perceive the virtual scene comfortably in full depth. In short, in contrast to "virtual reality", we seek "just enough reality".

Our thinking is motivated in part by an analogy with color vision. The Helmholtz tricolor model of color vision continues to serve well for all practical applications of color perception synthesis, e.g., photography, printing, and cathode ray tube displays. But in parallel with the straightforward and essentially physical Helmholtz model, there is Land's partly psychological "retinex"[13] differential theory, and the experiments that bear it out. Land showed, for example, that minutely disparate (in color space) separations, e.g., a pair of photograph made in the light of two spectral lines (the yellow sodium D-lines) just a few angstroms apart, can be displayed so as to adequately stimulate perception of the full visible color spectrum present in the original scene. This encourages us to suggest the possibility that, in an analogous fashion, minute perspective disparities may be adequate to stimulate perception of the full depth range in a complex real world scene.

To study these issues we generated image data sets of a still life consisting of a small statue of the cartoon cat “Garfield” against a solid background (roughly textured columns of variously colored modeling clay). The scene was photographed with telephoto, normal, and wide-angle lenses, each at 1 mm intervals up to ±20 mm perpendicularly displaced from the centerline, with and without center-of-interest compensation. (Center-of-interest compensation could be accomplished mechanically with this apparatus because the camera had been modified to allow left-right shifting of the CCD with respect to the optic axis of the lens.) Stereopairs can thus be created dynamically, and sequences of them animated, with interocular separations of 0 to 40 mm. The number of pairs that can be created obviously decreases with increasing interocular separation: there are 41 “pairs” with 0 mm interocular separation, 40 pairs with 1 mm, 39 with 2 mm, and so forth, down to 1 with 40 mm interocular separation. The quantitative experiments described in Sections 3 and 4 use the data taken with the wide-angle lens and with center-of-interest compensation. Some examples are shown in Figure 1.

Figure 1: Representative images from the “Garfield” image data set, reduced from color to monochrome only for illustration. (Above) The left image is a left eye view, the center image is a right eye view, and the right image the difference between them. Interocular separation is 40 mm; center-of-image compensation results in on-screen disparities that are nevertheless small, as can be seen in the difference image. Readers who can parallel “free view” should easily see the left and center image pair in stereo. (Below) Pictures of the “Garfield” scene with telephoto (left), normal (middle), and wide-angle (right) lenses at corresponding long, intermediate, and short distances from camera to scene. Distance and focal length are adjusted so that the each image is about the same angular size on viewing. But notice the relative “flatness” at the left, the relative “depth” at the right.

As is evident in the three views, illustrated by the bottom set of images in Figure 1, as the focal length of the lens is progressively reduced, and the distance to the scene correspondingly reduced to keep the image more-or-less the same size, perspective distortion is increased. This constitutes a secondary cue that enhances depth perception. Microstereopsis (our term for stereo imagery in which the actual or virtual interocular separation is unusually small) is most effective when perspective distortion and other secondary depth cues are exploited to the hilt.

“Center-of-interest compensation” is also exploited to enhance the effect while reducing the strain and time required for the viewer to fuse stereo imagery. There are three basic ways to do this; they can be combined linearly to achieve the desired net effect. The first way is to converge the cameras to overlap the fields-of-view and to zero the disparity in the vicinity of the scene's center-of-interest. This method is discouraged because the resulting keystone distortion causes vertical disparities that conflict with comfortable viewing. The second way is to use parallel camera axes and shift the images left-right to zero the disparity at the center-of-interest. This results in pleasant-to-view stereo, but the usable image width is smaller than the original image width by the size of the shift, making the aspect ratio of the viewable image a function of the distance to the center-of-interest. The third way is to use parallel camera axes and to shift the camera sensors (e.g., CCDs) outward to overlap the fields-of-view at the distance to the center-of-interest. This is the perfect solution; it's only drawback is that the cameras have to be physically modified. Given a "center-of-interest finding algorithm", any of the three would be easy to automate via a simple low computational-overhead shifting algorithm.

3. HOW MUCH IS “JUST ENOUGH”?

Developers and users of stereoscopic applications recognize that there is an inverse relationship between disparity and ease of stereopair fusion. For example, in Hiruma's "Accommodation Response to Binocular Stereoscopic TV Images" we read [4]: "for close viewing [meaning 'for tasks requiring serious concentration', vs. for example, entertainment] the disparity should be only as big as requested". In this section we report early pilot experiments that demonstrate that surprisingly small disparities are adequate to stimulate binocular stereopsis. We also note that this "microstereoscopic" imagery is described by most subjects as more comfortable to watch than conventional stereoscopic imagery.

Figure 2 summarizes ten viewers' ability to perceive microstereopsis based on their pair-ordering of the "depth" or "3D-ness" that they perceive in pairs of stereoscopic pictures displayed side-by-side. We presented each viewer with the two stereo images and asked him or her to indicate whether the left picture, neither picture, or the right picture seemed to "have more depth"; the subject is given no additional guidance as to what “having more depth” means. The pictures were randomly chosen from the “Garfield” image data set by a computer program that picked images on-the-fly from a set of 41 that were taken 1 mm apart at a working distance of about 30 cm with a 12.5 mm focal length lens. Each viewer was shown 80 pairs of stereo images in two sets of 40. In the first 40, one image was always flat, i.e., the left-eye and right-eye sub-images were actually identical. In the second 40 both were nominally stereo, although by chance sometimes one or both might have zero disparity. Within each 40 there were 5 sequences of 8 x 2 images. Each of the 8 was drawn from a random Poisson-weighted disparity distribution. The first 8 had a mean camera interocular separation of 4.5 mm, the second 8 had a mean of 3.5 mm, and so on down to the fifth 8, which had a mean of 0.5 mm. The flat images in the first 40 were taken from perspectives randomly displaced from the midpoint of the data set by the same statistical distribution that randomizes the disparities. The subjects were told that the task "starts easy and gets more difficult as it progresses", but they were not told that in the first 40 sets one of the pictures was always flat.

It can easily be seen in Figure 2 that, across the sample population, a stereo pair corresponding to as little as 1 mm of interocular separation can reliably be distinguished from an image that is actually flat. These data were collected with only ten subjects, and must be considered anecdotal pending confirmation with additional subjects, appropriate controls, and appropriate tests of statistical validity.

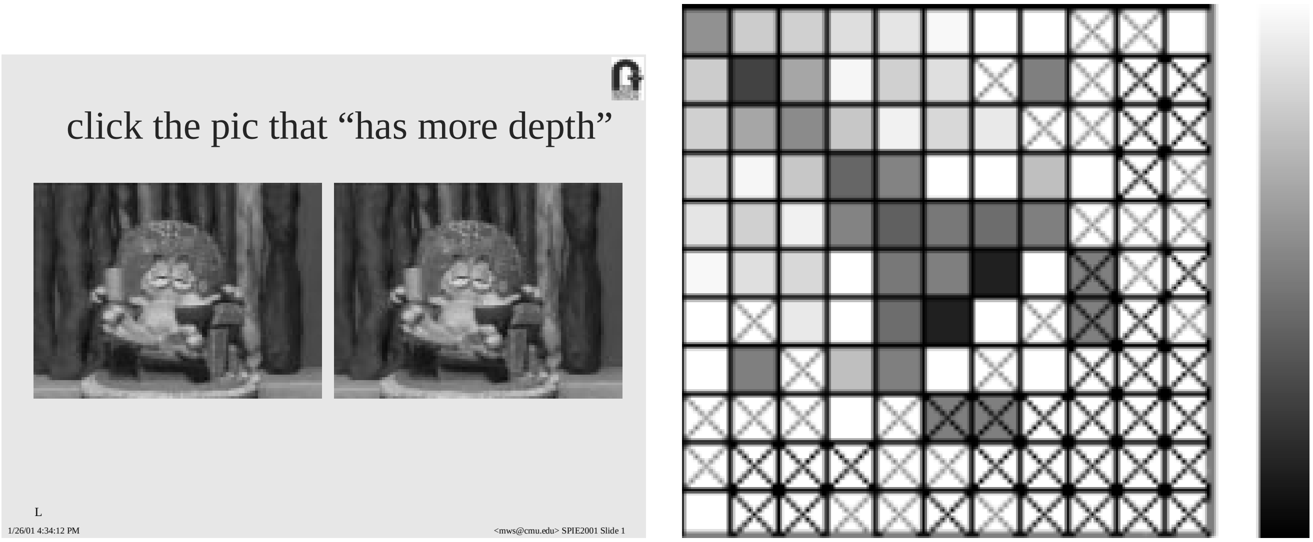

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Figure 2: (Left) Example of the screen presented to subjects in the depth pair ordering experiment. (Right) Depth pair ordering summary, averaged over the 10 subject individuals, symmetrized across the diagonal. Origin is at the upper left, where both displayed stereo pictures have zero interocular. From left to right the left picture interocular increases from 0 to 10 mm. From top to bottom, the right picture interocular increases the same way. The gray level scale indicates 0-100% correct identification from black to white. Xs indicate combinations of (left picture interocular, right picture interocular) that did not occur in the set of experiments.

4. PERCEPTIONS OF CROSSTALK

In the literature of 3D-display systems the terms "crosstalk" and "ghosting" are often used as if they are synonymous. In reality they are not: "crosstalk" is the electrical or optical mixing of left- and right-eye image channels, whereas "ghosting" is a particular mode of perception of imagery that has been degraded by crosstalk. It is clear that other modes of perception are possible; for example, crosstalk may be so small as to be imperceptible. Even when crosstalk is as large as it possibly can be, as when an eyewear-based 3D-stereoscopic display is viewed without eyewear, the crosstalk may still be imperceptible, e.g., if the on-screen disparities are very small. Now, we ask, if the crosstalk is as large as it possibly can be, and the on-screen disparity is increased smoothly from zero to the point where the crosstalk is first perceived, *how* is it perceived? In particular, we ask, is it perceived as *ghosting*, or is it rather — our hypothesis — perceived only as degrading of the spatial resolution, i.e., as *blur*?

We initially conducted a simple test of our hypothesis by modifying a conventional LCD shutter-glasses controller to give it adjustable crosstalk. The protocol was to show a subject a stereopair taken with normal interocular separation, and to instruct him or her to increase the crosstalk adjustment until ghosting became perceptible. At this crosstalk level, the subject was then shown image pairs with reduced interocular separation. The experiment was repeated with three informally recruited subjects, leading to the preliminary conclusion was that there is indeed a region in which crosstalk is relatively large, interocular separation is relatively small, and in that region crosstalk is perceived as blurring rather than ghosting and scene depth is perceived accurately and comfortably.

To confirm quantitatively the existence of a region in which on-screen disparity is large enough to stimulate depth perception and small enough to be perceived as blur rather than ghosting, and, if it exists, to map its borders, a program was written to display stereopairs with variable interocular separation and variable crosstalk. A stereopair with a selected interocular separation, e.g., 5 mm, is randomly selected from a subset of the “Garfield” data set (the above-described 41 images collected with 12.5 mm lens, 30 mm object distance, and mechanical center-of-interest compensation), a crosstalk percentage (e.g., 0%

-> the baseline crosstalk inherent in the display hardware, 25% -> 1:3 mixture of left image in right eye view and vice versa, 50% -> left eye view and right eye view are the same mix of left eye image and right eye image, 100% -> completely pseudoscopic except for the baseline crosstalk inherent in the display hardware). A subject is asked to place each image in one of two *stereo perception classes*, {~stereo | stereo}, and one of two *crosstalk perception classes*, {~ghosting | ghosting}, where the tilde (~) signifies "not". For each classification a point is plotted with a symbol that labels which of the four combined classes {~stereo, ~ghosting|}, etc. The outcome is summarized for three informally selected subjects in Figure 3.

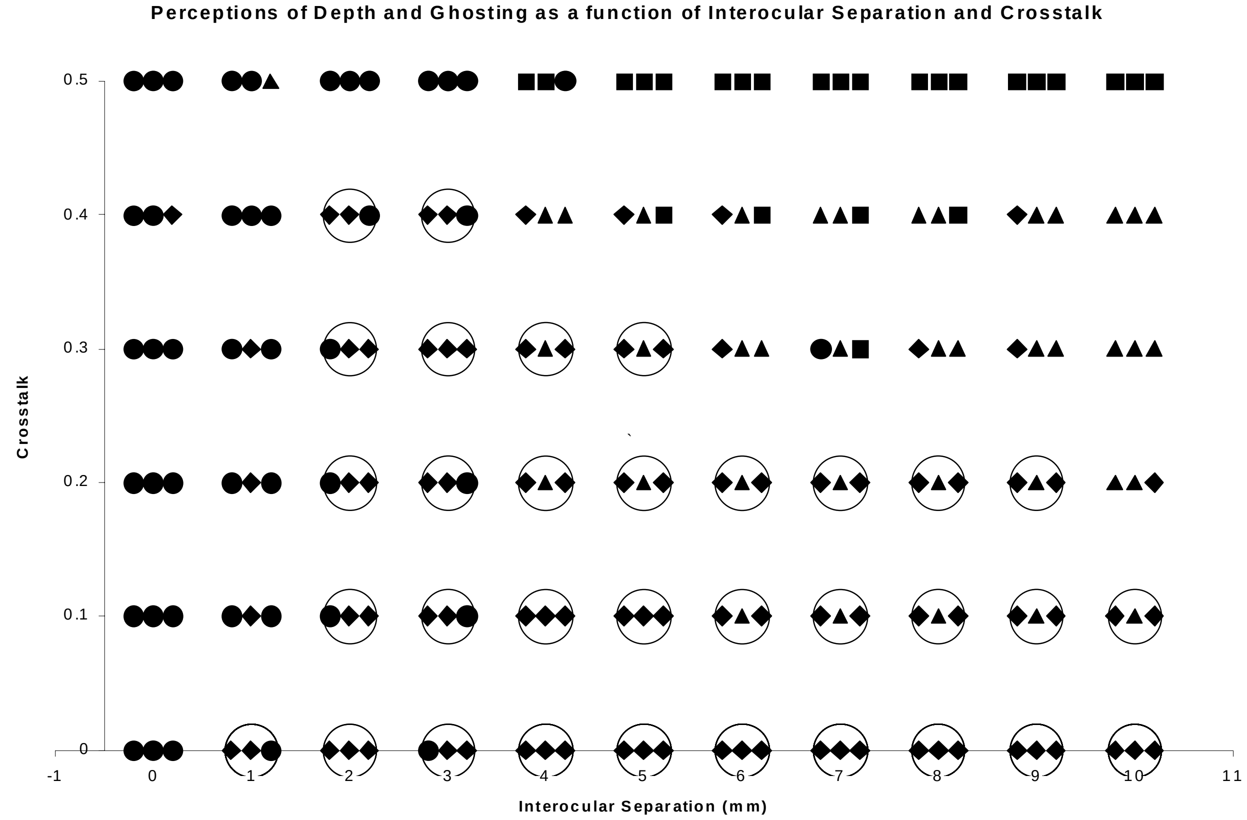

Figure 3: Perceptions of stereo and crosstalk. Stereopairs are generated from the "Garfield" data set with randomly selected interocular separation and crosstalk percentage (see text for quantitative definition). Subjects are asked to classify each displayed stereopair in one of four classes corresponding to perception of the image as being flat or in stereo and ghosted or not ghosted. Legend: {stereo, ~ghosting}->DIAMOND, {stereo, ghosting}->TRIANGLE, {~stereo, ~ghosting}->CIRCLE, {~stereo, ghosting}->SQUARE. LARGE OPEN CIRCLES around a group of three small symbols denotes a group in which two or three out of three subjects agree that the image is in stereo and without ghosting. Note the bell shaped region of LARGE OPEN CIRCLES wherein this desirable condition is realized. This region corresponds to the perception of stereo without the perception of ghosting despite the presence of crosstalk. When the crosstalk is 10% (i.e., the pixel-by-pixel blending of 90% the intensity of the "correct" image with 10% of the intensity of the "wrong" image), stereo without ghosting is definitively perceived whenever the interocular separation is less than or equal to about 5 mm. When the crosstalk is as much as 40% (i.e., the left eye is shown 60% left eye image and 40% right eye image), interocular separations of 2 and 3 mm still stimulate stereo perception without substantial perception of ghosting! Note the reasonableness of this shape: as expected, even when the interocular separation is very small indeed, i.e., 1 mm, stereo perception is suppressed by sufficient crosstalk, even though when the interocular separation is this small the crosstalk is perceived as slight foreground and background blur rather than as ghosting.

Inasmuch as these data were collected with only three informally selected subjects, this result must be considered anecdotal pending confirmation with additional subjects, appropriate controls, and appropriate tests of statistical validity.

5. PROSPECTS FOR ZONELESS AUTOSTEREOSCOPIC DISPLAYS

The existence of a perceptual region in which disparity is small enough that — in the presence of crosstalk — it is perceived as blur, yet it is nevertheless large enough to stimulate binocular stereopsis, suggests the possibility of new classes of zoneless autostereoscopic displays. Zoneless displays would be achievable because of the tolerability of crosstalk between left and right eye channels. Under these circumstances it is not necessary to completely separate the left-eye and right-eye channels; it is adequate that an appropriate bias be created, such that the left eye "sees more" (e.g., via an illumination disparity) of the left-eye image than it sees of the right-eye image, and vice versa. This kind of bias can be achieved by means of a suitably non-lambertian screen over an otherwise conventional display. In a time-multiplexed system the bias (e.g., illumination gradient) would be made to alternate directions synchronously with the alternation of left-eye and right-eye images on the display. Practical implementations could be achieved with electronically switched louver filters based on, e.g., suspended particle displays, LCDs, and other technologies. [8][10][11]

At this time we can describe only in a general sort of way, without yet being able to give numerical values for physical or psychophysical parameters, as these will have to be determined by future experiments, how we would go about engineering this system. One approach is simply to illuminate the display screen (if it is transmissive, e.g., an LCD) or filter it (if it is emissive, e.g., a CRT) in an angular pattern that looks brighter or dimmer depending on the viewing angle, i.e., it is “non-lambertian” in a particularly designed sort of way. The two eyes thereby see different screen brightnesses corresponding to the different azimuths from which they view the screen.

Passive screens with precisely this property (but with stronger gradients than we probably want) are actually commercially available, e.g., 3M's "Privacy Shield" material for bank ATMs and laptop computer screens (e.g., for frequent flyers who want their screens to be invisible from the adjacent seat). This screen material is a microfabricated "venetian blind"; the generic device is called a louver filter, the concept of which is illustrated in Figure 4.

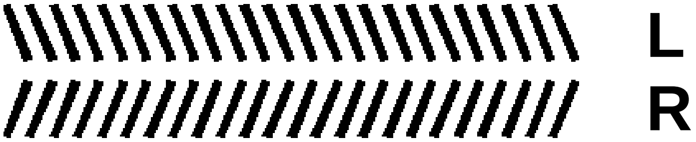

Figure 4: Two states (R, L) of louver filter. Looking up from this caption toward the filter, in the R state the bias favors the right eye, in the L state it favors the left eye.

Two engineering challenges remain to be overcome to turn this idea into a practical microstereoscopic display: (1) we need an electronically switchable louver filter, and (2) the gradient needs to be strong enough between the eyes that sufficient bias is achieved, but not so strong over the full range of viewing azimuth that the illumination difference between the two states is annoying. Depending on the outcome of measurement of the psychophysical factors, this tradeoff may limit the display's useful range of viewing angles. On the other hand, even in the worst case the idea should nevertheless be workable for viewing the display more-or-less head-on, and even in that worst case it should still be far less restrictive about head position, in both azimuth and range, and than are the lenticular and barrier displays currently on the market.

We suggest, for example, that an electronic louver filter can be implemented using suspended particle display technology 0 as illustrated schematically in Figure 5. It uses opaque dielectric particles with permanent dipole moments suspended in a transparent dielectric liquid. The particles are oriented as desired by an electric field produced by electrodes patterned on the windows. This technology is currently in pilot production for "smart windows" for automatic control of indoor sunlight. It seems to require only more complex electrode patterning and driver electronics to make it into an electronic louver filter.

Other possibilities, e.g., liquid crystal display based electroholographic devices, and also under consideration.

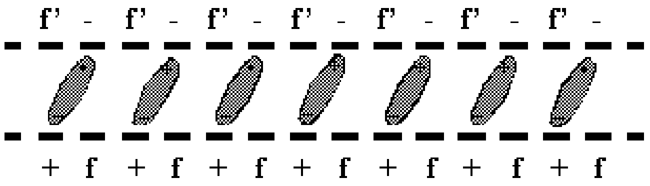

Figure 5: Electrode pattern and polarization required to produce the L state of Figure. Transparent electrodes are held at positive (+) or negative (-) voltage, or allowed to float (f,f’). Elongated opaque suspended particles in liquid carry a permanent dipole moment. Interchanging + and f on the lower electrode, - and f’ on the upper electrode changes device to the R state. Note wave-like character of activation.

6. CONCLUSIONS

We suggested and demonstrated (with 10 subjects in an informal but quantitative experiment) that very small on-screen disparities, obtained by the combination of very small interocular separations and center-of-interest compensation (“microstereo”), are adequate to stimulate stereo perception. We further suggested and demonstrated (with one subject in an informal but quantitative experiment) that, because very small on-screen disparities are perceived as unobjectionable blur rather than as objectionable ghosting, microstereopsis is more tolerant of left-right channel crosstalk than is typical stereo. Based on this observation, we propose for future research and development a class of zoneless autostereoscopic displays.

ACKNOWLEDGMENTS

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