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A purely temporal transparency mechanism in the visual system

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Abstract. I report evidence for a purely temporal perceptual transparency mechanism. Rapid alternation of two images in the same location can result in the simultaneous experience of both, accompanied by a sense of transparency. This is true even when the sum of the two images does not appear transparent, which suggests that the percept is not mediated by the static transparency processes. At slow rates, alternating gratings were experienced as successive. As the rate was increased, by 8 Hz observers experienced the gratings as simultaneous. The rapidly alternating gratings are apparently processed separately before being combined for awareness by a process that integrates over about 120 ms. A final experiment tested whether the common presentation time of different parts of an image in alternation with another would cause the parts to perceptually bind. Observers did not distinguish between a rapidly alternating intact grating display and one in which halves of the display were exchanged in time. In other words, temporal binding across space did not occur. The temporal transparency phenomenon, in addition to informing theories of transparency and the dynamics of visual processing, may also be useful for the creation of transparent displays for electronic devices.

1 Introduction

Gazing at a flower garden through a window streaked with rain, one is aware of the properties of two surfaces in one direction, albeit at different depths. In this situation, monocular (Metelli 1974) and binocular cues are used by the visual system to recover the lightnesses of the two surfaces and produce the experience of transparency for the closer surface.

For decades, researchers have conducted experiments to elucidate the mapping between binocular and monocular cues and our transparency percepts (eg Anderson 1997; Metelli 1974). However, one cue to transparency has garnered little attention or scrutiny.

In 1939, Bartley noted that rapid alternation of two spatially uniform patches of differing brightness can result in the experience of both brightnesses continuously, with one patch appearing transparent. This showed that temporal alternation provides a cue to transparency. However, I have found no acknowledgements of this in the transparency literature. Although this is most likely due to ignorance of Bartley's work, it may also stem from a notion that transparency of a flickering light is only a curiosity which does not show that temporal alternation is a transparency cue on the order of static binocular and monocular cues.

Here, I show that this temporal cue is not confined to flickering lights. Rapid alternation of two *patterns* can also yield the perception of both stimuli continuously, with one appearing transparent. I therefore argue that this cue to perceptual transparency should be taken more seriously, and perhaps garner a similar level of interest as temporal cues to subjective grouping (Lee and Blake 1999; Leonards et al 1996). The transparency may be a consequence of exceeding the temporal resolution of high-level vision or attention: rapidly presented stimuli are not experienced as distinct events (He et al 1997; Holcombe et al 2001; Verstraten et al 2000).

After providing evidence in experiment 1 that the sense of transparency which accompanies rapid alternation of two gratings cannot be explained by static cues for transparency, in experiment 2 I explore the temporal properties of the mechanism which combines successive patterns for awareness, and in experiment 3 I begin to investigate the role of common presentation time in grouping for transparency.

Some demonstrations of the temporal transparency phenomenon are available from the author's website (http://www-psy.ucsd.edu/~aholcombe) or by contacting the author, and from the *Perception* website (www.perceptionweb.com/perc1101/holcombe.html). The demonstrations are archived on the CD ROM supplied with issue number 12 of the journal.

2 Experiment 1

The first purpose of experiment 1 was to establish that observers do experience two sets of bars when viewing two gratings that are rapidly alternating (experiment 2 will show that not only are they both experienced, they are both experienced continuously). The second purpose was to test whether the experience of two sets of bars could be attributed to the previously documented mechanism that yields transparency from static cues such as X-junctions and particular spatial luminance relations (Metelli 1974).

With two arbitrary images, the sum (temporal integration) of the two images typically will contain cues such as X-junctions and luminance relations consistent with Metelli's rules for transparency. Therefore, during rapid image alternation, it is possible to attribute a percept of both images to internal summation followed by use of the static cues. In this experiment, I eliminated this possibility by choosing two patterns whose sum does not appear transparent [similar stimuli were used for a different purpose in Holcombe and Cavanagh (2001)]. The fact that the display nonetheless appears transparent suggests that the transparency results from a temporal cue. Other displays were used to address variations of the theory that the transparency is due to the static transparency mechanism.

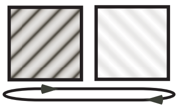
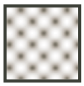
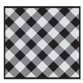
2.1 *Method*

2.1.1 *Observers*. Each of nine observers had normal or corrected-to-normal vision, and all had some experience with psychophysical experiments.

2.1.2 *Stimuli*. The CRT had an 85 Hz refresh rate and was linearized with a color look-up table. The background of the screen was filled with static noise (random white 63 cd m^{-2} and black $\sim$1 cd m^{-2} dots).

Figure 1 depicts the displays. Display A, the grating alternation stimulus, consisted of two sinusoidal gratings of equal amplitude (19 cd m^{-2}) but differing mean luminance (19 and 41 cd m^{-2}) and opposite orientations (45° clockwise and counterclockwise from vertical) alternating at 14 Hz. The gratings were 1.46 cycles deg^{-1} and were windowed by a virtual square 3.4 deg on a side. A yellow fixation point 0.2 deg in diameter was presented in the center of the pattern throughout all the trials. To occlude dynamic noise introduced by a defect in the graphics card, a rectangular yellow strip 0.2 deg high and 5 deg wide, aligned with the bottom left edge of each stimulus, appeared in all displays. It had no effect on the appearance of the stimulus and in any case was present in all conditions. All of the displays in this experiment utilized gratings with the same spatial frequencies, orientations, and window size as those of display A.

Observers also rated a modified version of A, termed display A_2, which was created by halving the contrast of the two gratings. Display B was created by first averaging the two gratings to create a plaid, as would occur if the visual system temporally integrated successive gratings. Then the plaid was increased in contrast so that the luminance range of the plaid B spanned that of the two gratings (9.5 $\rightarrow$ 50.5 cd m^{-2}). In display B′, display B was rapidly alternated (14 Hz) with a uniform field with luminance the mean of the two gratings (30 cd m^{-2}). Thus integrating B′ over one cycle resulted in the same pattern with the same luminances and contrast as integrating over a cycle of A. Display C was created by temporally integrating square-wave versions

Judgment of brighter component (left versus right)/% correct	Brighter component perceived in front/% trials		Display
94 ±16	28 ±12	A	
50 ±35	**61 ±11**	B	 static average of the two stimuli in A, boosted in contrast
44 ±39	**39 ±11**	B′	static average (B), flickering
38 ±33	**50 ±12**	C	 square-wave version of B
61 ±33	**55 ±10**	C′	display C, flickering
100 ±0	100 ±0	D	unambiguous static sine-wave plaid
100 ±0	100 ±0	E	 unambiguous static square-wave plaid
77 ±36	**17 ±12**	A_2	display A, presented at half-contrast

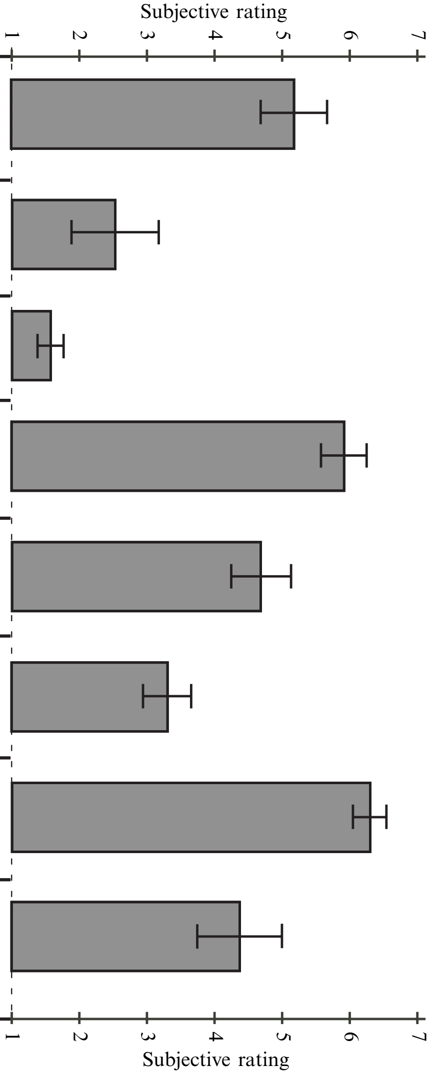


Figure 1. In experiment 1, nine observers viewed eight displays, schematized in the figure. For each, they rated the extent to which they experienced two sets of perpendicular bars (a '7' rating) versus one set of bars or no bars (a '1' rating). This indexed the strength of the transparent percept of two sets of bars, and the mean ratings and standard errors for each display are plotted in the bar graph. In half the trials, the stimuli were created from grating components for which the leftward-tilted one was brighter, and in the other half of trials the rightward-tilted component was brighter. Observers reported whether the leftward-tilted or rightward-tilted bars appeared brighter, and the mean percentage of trials and standard error in which this corresponded with how the stimuli were created is tabulated in the first column. Observers also reported which set of bars appeared to be in front, and the percentage of trials in which the brighter stimulus component was reported, and the corresponding standard errors are tabulated in the second column. Figures that are within one standard error of chance (50%) are shown in bold type.

of the two alternating gratings, and scaling up the contrast to equal the luminance span of A and B. In display C′, C was alternated at 14 Hz with a uniform field of the same mean luminance (30 cd m^{-2}).

Display E was similar to display C in that it was the sum of two perpendicular square-wave gratings with differing mean luminances (17 cd m^{-2} and 25 cd m^{-2}) but instead of being vertically symmetric, the symmetry was broken by using gratings of differing amplitudes (22 and 50 cd m^{-2}, respectively). Display D was created in the same way as display E except that the component gratings were sine-wave instead of square-wave.

Two versions of each of the displays were created—one in which the darker pattern (or pattern component in the case of the displays created by averaging two components) was tilted rightward and one in which the darker pattern was tilted leftward. The brighter pattern was perpendicular to the darker pattern in each case.

2.1.3 *Procedures.* Observers viewed a CRT from a distance of 77 cm, wore an eye-patch over one eye, and fixated on a dot centered on a 0.4 deg yellow spot centered on the stimuli. Each version of each display was presented once and all were presented in pseudo-random order.

For each display, the observers' first task was to describe a certain aspect of their subjective experience on a scale of 1 to 7: '7' indicating that they experienced a compelling percept of two sets of bars tilted in opposite directions, and '1' indicating they experienced only one set of bars or no bars. At the beginning of the experiment, observers were shown relatively unambiguous stimuli to anchor their ratings. Observers were shown A at a very slow (0.43 Hz) alternation rate, such that they experienced first the dark bars, then the bright, etc, and told that such a stimulus should receive a rating of 7. Then they were shown E, which they all reported as white bars presented transparently on black bars, and told it should receive a rating of at least 6. They were told 6 rather than 7 to allow for the possibility that other displays would create a stronger sense of two sets of bars than is yielded by the 2-D static pictorial cues of E. After reporting their rating, observers were asked to report which set of bars appeared brighter, the leftward-tilted set or the rightward-tilted set. Finally the observers were asked which set of bars appeared closer to them in depth. The observers were told to guess or respond randomly if they did not perceive two sets of bars, and they were further warned that sometimes the questions might seem nonsensical but it was necessary to ask the same questions for all the stimuli.

2.2 *Results and discussion*

Although the sums of sine waves (B, B′) were not seen as two separate patterns, the alternating sine-wave display (A) was. Observers' mean ratings for perceiving display A as two sets of bars fell within the range of ratings for C and C′ (the square-wave plaids), indicating that the effectiveness of the temporal alternation cue was similar to that of the static cues of C. The much higher rating for A than for B and B′ discredits the notion that the percept of both sets of bars results from cues not inherent in the temporal alternation. According to this notion, the transparency perceived in A occurs because the rapidly alternating patterns sum internally, and static cues subsequently allow decomposition into separate surfaces. But, to the contrary, when viewing the sum (B), observers experienced a qualitatively different percept than that of A. Furthermore, observers' reports of which set of bars appeared brighter in A corresponded to the brighter grating in 94% of trials. This could not have occurred if the transparency was based on first temporally integrating the successive stimuli together, for this would result in an ambiguous stimulus that contains no cue as to which component was brighter. The ambiguity of the sum was confirmed by observers' approximately chance performance (50%) in reporting which bars were brighter for displays B and B′ (first column of figure 1).

However, a variation of this criticism would add the idea that a nonlinearity precedes the putative internal temporal integration, yielding a distorted average, which might then be decomposed into separate layers by the static monocular mechanism. Anstis and Ho (1998) found that the apparent brightness of a flickering light did not correspond to the average of the two phases but, instead, overweighted the higher-contrast phase. We attempted to create the possible distorted average pattern of display A by asking three observers to match the appearance of each of the gratings during rapid alternation by adjusting the brightness, contrast, and sharpness of a third grating. Subjective ratings indicated that the sum of these matches was perceived as significantly less transparent than the alternating display, even when the sum was flickered to mimic the percept of the alternating gratings.

Further evidence against an internal-sum or distorted-sum explanation of the results comes from the observers' perception of depth order in the displays. Whereas with the static stimuli observers quite consistently reported that the bars perceived as brighter were also perceived to be in front, in display A the brighter bars were usually perceived in back (figure 1, column 2). If the transparency in the rapid alternation case were explained by a kind of summing, then the same depth ordering would be expected in the two cases.

The reason that the rating of display A was somewhat lower than that of E may be due to the presence of flicker in display A. The transparency ratings for the static stimuli of B and C were significantly diminished by adding flicker (displays B′ and C′). The addition of flicker to B and C may act to reduce transparency by lowering the time-averaged contrast, and this may also explain the difference between A and E. Lowering contrast seems to lower mean transparency ratings (B is lower than A). Therefore, the comparison of A and E may not be fair, because A has only half the time-averaged contrast of E, and this may explain the lower rating for A. Alternatively, it may also be that the temporal cue is not as strong a cue for transparency as static pictorial cues.

One more cause for the lower rating of display A compared to E may be the presence of a monocular rivalry or fading effect. Some observers spontaneously reported that the set of bars they were not attending to sometimes faded or became less conspicuous.

Overall, the results suggest that, rather than reflecting internal temporal integration followed by the use of static monocular cues to yield transparency, the temporal alternation causes the visual system to represent two different signals at each point in the stimulus, just as a simple flickering light is seen as two different brightnesses experienced simultaneously (Bartley 1939).

3 Experiment 2

For the rapidly alternating (14 Hz) gratings of experiment 1 to be perceived, the individual frames must be resolved by the visual system. However, for them to be perceived as continuously available rather than successive, some mental process must temporally combine their representations prior to visual awareness. Here the integration time of that process is measured by varying the alternation rate to find when the patterns seem simultaneous rather than successive.

3.1 *Method*

3.1.1 *Observers.* The same observers were used as in the previous experiment, and the experiment was run in a session which immediately followed the previous one.

3.1.2 *Stimuli and procedures.* After participating in experiment 1, in the same session and with the same viewing conditions observers viewed display A of figure 1 presented at a variety of alternation rates, without an ISI. As in experiment 1, one trial of each version of display A was presented: one in which the rightward-tilted grating was the brighter grating, and another in which the leftward-tilted grating was brighter. These two versions were crossed with several presentation rates to generate the trials, which were presented in pseudo-random order. The presentation rates are shown along the abscissa of figure 2. Under no time pressure, observers viewed each stimulus until they verbally reported a rating, which could range from 1 to 7: '1' meant the alternating gratings were experienced as strictly successive, '7' meant that they were each experienced continuously and simultaneously. At some rates, pilot studies indicated that one grating might be experienced as stable while the other flashed on top of it (Holcombe, in preparation), or that one grating would fade while the other appeared constant, and the percept could fluctuate among these possibilities. Thus, intermediate ratings were allowed so observers could signal that they experienced these somewhat intermediate percepts. To reduce variability in how observers used the rating scale, before the trials began observers viewed display A at a very slow presentation rate—0.43 Hz, and were told they should give that display a 1. Subsequently, the observers were shown display E and told that it merited a 7 and then shown display C′ and told that it also deserved a 7. The experimenter pointed out that display C′ shows that the percepts of simultaneity and flicker are not mutually exclusive.

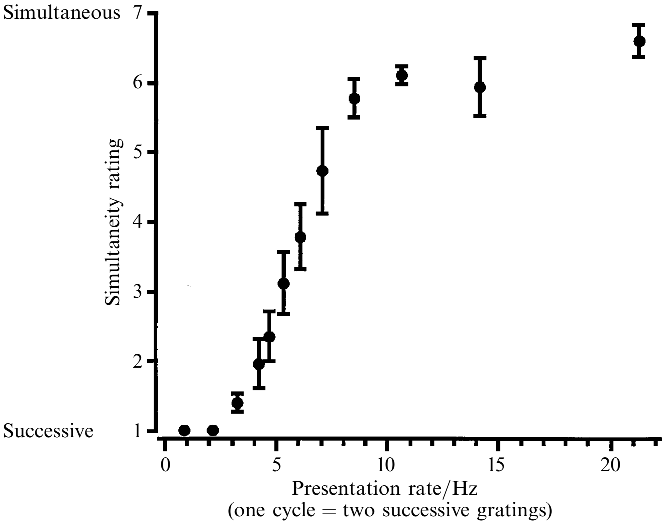


Figure 2. In experiment 2, nine observers viewed display A schematized in figure 1, presented at a variety of presentation rates. For each presentation rate, observers provided a subjective rating from 1 to 7, '1' meaning the perpendicular bars were perceived successively, '7' meaning they were both experienced continuously and simultaneously.

3.2 *Results and discussion*

Observers' reports of which bars appeared brighter accorded with the physical stimuli in over 94% of trials for all but the fastest rate, 21 Hz, for which the accuracy was 89%. This certifies that observers' perception resolved the gratings, for if they had perceived the sum, their performance would have been at chance (which was verified by their 44% mean correct in a 42 Hz condition).

Figure 2 shows that at slow rates observers give '1' ratings, and between 3 Hz and 8 Hz their ratings rapidly increase towards '6', asymptoting at about 10 Hz. This suggests that the process which combines the gratings before awareness integrates over a period on the order of 100 ms.

Note that the continuous experience of both patterns at high rates cannot be due to persistence of very-low-level vision. If it were simply the persistence of photoreceptor activation, for example, when observers experienced the gratings as simultaneous, they would experience something like display C rather than transparency (as shown in experiment 1). Instead, persistence (or integration) of a higher-level representation must be occurring.

A large body of previous work on visual temporal resolution shows that most percepts reflect processes with a temporal resolution of less than 10 Hz. These include apparent motion (Verstraten et al 2000), judgments of the relative temporal phase of adjacent flickering lights (He et al 1998; Martini and Nakayama 2000; Ramachandran and Rogers-Ramachandran 1991), judgments of temporally cooccurring spatially separated features (Holcombe and Cavanagh 2001), the perception of acceleration (Werkhoven et al 1992), some aspects of high-level motion perception (Lu et al 1999; Lu and Sperling 1995), and induced motion (Nakayama and Tyler 1978) and brightness effects (De Valois et al 1986). The variety of percepts with a slow cut-off suggests the presence of a slow visual processing stage before awareness. Perceptual qualities with high temporal resolution, such as motion, likely reflect the output of low-level detectors which extract selected portions of high-temporal-frequency information (eg motion direction) and label them for awareness.

4 Experiment 3

The fact that the rapidly alternating gratings appeared transparent implies that the gratings were at least partially processed individually by the visual system before being combined for awareness. The visual system may group stimuli which occur at a common time into the distinct layers of the transparent percept. Alternatively, the assignment of the stimuli to distinct layers may be unrelated to cooccurrence in time.

Consider the split-grating stimuli depicted in figure 3. The stimuli depicted in figure 3b were created from those of figure 3a by switching the presentation times of the bottom halves of the successive gratings. If common presentation time causes perceptual binding, then the displays depicted by figures 3a and 3b should look different. This should also cause the displays depicted by figures 3c and 3d to look different from each other.

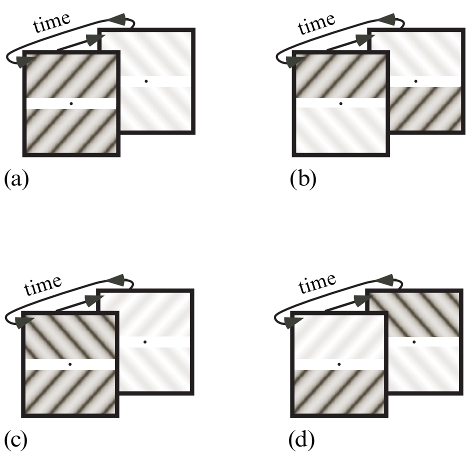


Figure 3. The displays used in experiment 3. The stimulus depicted in (a) was created from display A of figure 1 by spatially splitting the two gratings and separating them by ~10 min of arc. The display depicted in (b) was created from (a) by switching the presentation time of the bottom halves of the two frames. Display (c) was created by reversing the orientations of the upper grating fragments of (a), and (d) was created by switching the presentation times of the upper grating fragments of (c). Observers did not perceive a difference between (a) and (b), or between (c) and (d).

4.1 *Method*

4.1.1 *Observers*. The same observers were used as in the previous experiment, and the experiment was run in a session which immediately followed the previous one.

4.1.2 *Stimuli and procedures*. The stimuli depicted in figure 3a were created by spatially splitting the gratings of display A in figure 1 and separating them vertically by ~10 min of arc. Figure 3b was created by temporally switching the bottom halves of the gratings of figure 3a. After participating in experiment 2, and with the same viewing conditions, observers were shown four different stimuli: those depicted in figures 3a, 3b, 3c, and 3d. The display of figure 3c was created by reversing the orientations of the upper gratings of figure 3a. Figure 3d was created by reversing the presentation times of the upper grating halves of figure 3c. Thus, the upper gratings could be either collinear or non-collinear with the bottom gratings of the same luminance, and the gratings of the same luminance could be presented at either the same time or different times. Each display was presented at 14 Hz and shown to the observers in pseudo-random order. For each display, they were asked to report which grating appeared to be in front in the top half of the display, which appeared to be in front in the bottom half of the display, and which gratings most grouped together between the two halves. Observers made the reports at their leisure while viewing the displays.

4.2 *Results and discussion*

Observers reported that the brighter bars in the top half of the stimulus appeared in front in 28% of the trials, and appeared in front in the bottom half of the stimulus in 39% of trials. The difference was not statistically significant and the numbers are comparable to the 33% found for display A in experiment 1. In all but two of all of the stimulus presentations (94%), observers reported that the sets of bars with common brightness grouped together. There was no tendency for gratings presented at the same time to group together. Indeed, in the two exceptions to the rule that the gratings of common luminance grouped together, it was not the gratings presented at the same time that grouped. Rather, those two trials constituted cases in which the brighter grating was collinear with the darker grating on bottom, and they grouped together despite being presented at different times. The indifference of observers' percepts to the temporal relationship of the upper and lower gratings is consistent with other findings that observers can only discriminate the relative temporal phase of spatially separated, alternating stimuli at rates less than 8 Hz (Holcombe and Cavanagh 2001; Ramachandran and Rogers-Ramachandran 1991). Although the temporal relationships of different parts of such stimuli may be represented at some stages of the visual system, they do not affect the percept.

5 General discussion

Rapid temporal alternation of two patterns can yield perceptual transparency. This is the case even when the sum of the two patterns does not appear transparent (experiment 1), suggesting that a previously unrecognized temporal mechanism mediates the transparency.

A reviewer of this paper suggested that the sense of transparency could be explained by a limited-temporal-blurring hypothesis, in which the system temporally integrates over much of, but not all of, a cycle, resulting in a rapidly oscillating percept in which first one pattern, then the other would be weighted more and thus appear to be of higher contrast. Aside from not being consistent with one's experience of the display, if this were occurring, one would expect observers to be able to do the temporal phase discrimination of experiment 3. In the condition where the top and bottom were out of phase, observers would perceive the brighter pattern on top to be stronger together with the darker pattern on the bottom, etc. Blake and Yang (1997) have shown that observers are sensitive to such contrast changes of different patterns that are synchronized across space. Yet observers did not perceive a difference between when the two grating halves were in phase versus out of phase, which is evidence against the reviewer's suggestion.

At slow alternation rates, the successive gratings were experienced successively, one after the other. As the alternation rate was increased, flicker was still perceived, but more and more the two patterns seem to be present continuously, with simultaneity ratings asymptoting by 8 Hz. This suggests that the system integrates over ~100 ms for visual awareness, which is consistent with the temporal resolution of a variety of percepts (see discussion of experiment 2 for citations). Rapid successive stimulus presentation may exceed the temporal resolution of high-level, attentive processing stages, preventing perception of successive stimuli as distinct events. Nevertheless, earlier processing stages continue to process the individual stimuli, which results in the perception of both patterns rather than their sum.

A consequence of exceeding attentive temporal resolution in experiment 3 was that across-space binding was lost: observers could not report which grating fragments were presented at the same time (see also Holcombe and Cavanagh 2001). This does not necessarily mean, however, that there is not a representation in the visual system of which features occur at a common time at these temporal frequencies. Motoyoshi and Nishida (2001) presented displays which contained dozens of patches reversing in orientation, which at each instant formed a texture border. They found that observers could perceive a texture border at rates well above 10 Hz, implying that at such rates the visual system did represent which features occurred together. The failure to discriminate between the displays of figures 3a and 3b in the present work suggests that the texture-border mechanism requires more than two texture elements to signal a border (see also Rogers-Ramachandran and Ramachandran 1998).

Unlike the perception of texture borders, the depth ordering and other characteristics of the transparent percept apparently reflect rules which do not depend on which features were presented together temporally. Bartley (1939) had an observation which begins to elaborate these rules. He reported that he only perceived transparency when the two phases of his flickering light straddled the background, suggesting a critical role for ON/OFF channels in the transparency (also for the possibly concomitant luster, Anstis 2000). Consistent with this, I have observed that alternating between two perpendicular gratings with the same mean luminance does not yield segregation into two layers. However, the equiluminant colored stimuli of Holcombe and Cavanagh (2001) do appear transparent, so segregation into ON/OFF channels cannot be the whole story. Future work should investigate the rules for perception of transparency in alternating displays and their relation to the rules for transparency from static and motion cues (Metelli 1974; Stoner and Albright 1998).

The conditions in which gratings presented in the same location but moving in different directions result in transparency have been the subject of extensive research (Castelo-Branco et al 2000; Stoner et al 1990). The mechanism which mediates transparency from temporal alternation may also, at least partially, mediate transparency in moving plaids. The transparency phenomenon of the present paper may be a degenerate case of a mechanism which evolved to support segregation of motion signals in the same area, just as the perception of flicker may be a by-product of detectors designed for motion perception.

In addition to the implications for theories of transparency and temporal binding in the visual system discussed above, the temporal-transparency phenomenon may also have significant practical import. In recent years, the high-technology industry has crammed more and more information into devices with smaller and smaller screens, such as personal digital assistants and web-enabled cell phones. Transparency provides one way to display more information in a given area, and temporal alternation of images has some advantages over the other methods for creating transparent displays. Unlike transparency based on binocular disparity, an ordinary display can be used for flicker-based transparency—no special glasses or mirrors are required. Unlike conventional monocular transparency, additional spatial context extending beyond the region of overlap between the two surfaces is not needed to create the impression of two different colors in the same location. Rapid temporal alternation may prove to be a useful addition to other cues for transparency.

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