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The anatomical locus of T-junction processing

James A. Schirillo

Department of Psychology, Wake Forest University, Winston-Salem, NC 27109, United States

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ABSTRACT

Inhomogeneous surrounds can produce either asymmetrical or symmetrical increment/decrement induction by orienting T-junctions to selectively group a test patch with surrounding regions [Melfi, T., & Schirillo, J. (2000). T-junctions in inhomogeneous surrounds. *Vision Research*, *40*, 3735–3741]. The current experiments aimed to determine where T-junctions are processed by presenting each eye with a different image so that T-junctions exist only in the fused percept. Only minor differences were found between retinal and cortical versus cortical-only conditions, indicating that T-junctions are processed cortically.

1. Introduction

1.1. Increment/decrement asymmetries and T-junctions

When two or more surfaces abut they form a junction which can provide a cue as to whether one surface belongs to adjacent surfaces, or if it occludes other surfaces within a scene. Consequently, studies of simultaneous contrast often use two- and three-dimensional stimuli to explore the effects of junctions on both perceptual grouping (Guzman, 1968; Todorovic, 1997; Waltz, 1975; Zaidi, Spehar, & Shy, 1997) and occlusion (Anderson, 1997; Guzman, 1968; Heitger, Rosenthaler, von der Heydt, Peterhans, & Kubler, 1992). This raises the question of where in the visual system T-junctions are processed.

Simultaneous contrast may be due to lateral inhibition, most often considered a retinal process (Cornsweet, 1970; Diamond, 1960; Jameson & Hurvich, 1961, 1964; Kingdom, McCourt, & Blakeslee, 1997; Nabet & Pinter, 1991; Shapley, Caelli, Grossberg, Morgan, & Rentschler, 1990; Wist, 1974) that uses center/surround ganglion cells to behave in an opponent fashion (Hartline, 1938; Ratliff, 1965). However, in sublayer B of the inner plexiform retinal layer, ON-center ganglion cells connect to bipolar cells, while OFF-center ganglion cells connect to bipolar cells in sublayer A (Glezer, 1995), suggesting that increments and decrements may be processed in separate neural channels (Shevell, Holliday, & Whittle, 1992).

Yet, simultaneous contrast has been explained as a cortical process as well. Braddick and Atkinson (1982) claim that different bandpass filters process low and high spatial frequencies separately, which then combine their signals cortically into a unified percept. This would make large black and white regions in a surround influence each other in a separate channel, independently of how they might each directly influence smaller enclosed central gray test and comparison patches.

As an example of a increment/decrement asymmetry Schirillo and Shevell (1996) used checkerboard displays (Fig. 1a) to show that an incremental test patch (i.e., one that was brighter than its uniform comparison surround) appeared dimmer on a checkerboard surround than on a uniform surround of the same space-average luminance. In their checkerboard display the test patch abuts the top of four T-junctions (Fig. 1a, red T's). This signals that the test patch is *occluding* the center of the checkerboard. Thus, the T-junctions may group the checks more to each other so that they tend to influence each other (Fig. 1a, blue arrow) more than they influence the test patch (Bonato, Cataliotti, Manente, & Delnero, 2003; Todorovic, 1997). Interestingly, Schirillo and Shevell (1996) found that decrements (i.e., when the test patch was dimmer than its uniform comparison surround) appeared identical on the checkerboard surround and uniform surround of the same space-average luminance. This led them to hypothesize that the lighter check is the stronger inducer for incremental tests because it serves as a luminance anchor, against which other luminance values are referenced (Gilchrist et al., 1999).

Melfi and Schirillo (2000) manipulated the standard checkerboard display so that both the light and dark check influenced the test patch equally (Fig. 1b). In this case, relative to the comparison surround test increments were perceived 8% darker while test decrements appeared 10% brighter. These results suggest that, with the aforementioned altered surround, increments group more strongly with the light regions while decrements group more with the dark regions.

E-mail address: schirija@wfu.edu

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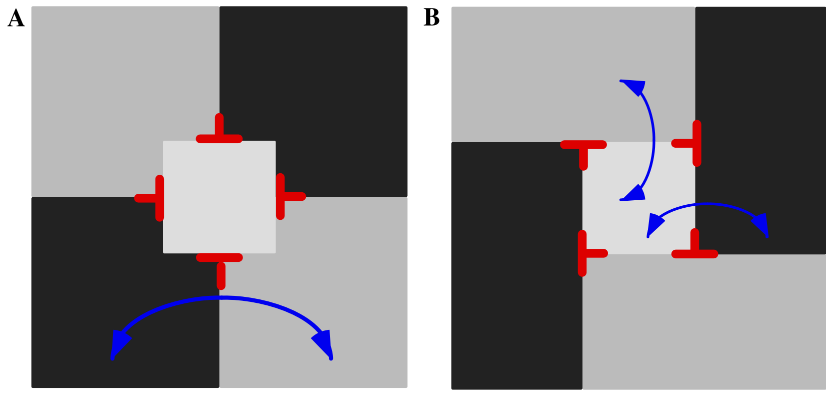


Fig. 1. (A) Schirillo and Shevell's (1996) checkerboard display, including T-junctions in red and maximum induction as a blue arrow. (B) Melfi and Schirillo (2000) shifted surfaces to alter T-junctions, making each surface as likely to maximize induction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

To explore further this effect of junction geometry, Melfi and Schirillo (2000) manipulated the junction geometry again so that either just the light regions (Fig. 2a), or just the dark regions (Fig. 2b) could be expected to influence the brightness of the test patch (based on the assumption that induction effects occur only between surfaces abutting at the stem of the T-junction). Their findings suggest that T-junctions enhances grouping across the stem and that grouping influences the amount of induction between test increments and the lighter regions, and test decrements and the darker regions. This suggests that the T-junction grouping mechanism proposed by Bonato et al. (2003) and Todorovic (1997) is due to another mechanism than Schirillo and Shevell's (1996) asymmetrical finding that the lighter check was the stronger inducer.

To better understand if these neural processes have distinct anatomical loci it is possible to exploit the logical necessity that information available only in a combined representation of the left-eye and right-eye monocular inputs cannot be processed at a level prior to the anatomical locus of binocular combination. Whittle (1965) has shown that attempts to fuse an increment and a decrement binocularly tends to produce rivalry. Altering such stimuli can therefore be used to explore differences in monocular versus binocular induction (Blake & Fox, 1973).

1.2. Binocular fusion and rivalry

One difficulty with binocular stimuli is that Levelt (1965a, 1965b) found that to maintain constant binocular brightness one must increase the weight assigned to one eye while decreasing the weight assigned to the other eye, so that the weights of the two eyes sum to unity. Levelt called this the *theory of complementary shares*. However, binocular subadditivity (or rivalry) is also possible. Rivalry occurs when the inputs from each monocular image compete for expression in the binocular percept. Three popular rivalry models are the vector sum model by Engel (1967, 1969, 1970), the centroid model by De Weert and Levelt (1974), and the quadratic model by Legge (1984) and Legge and Rubin (1981).

Engel's vector sum model (1967, 1969, 1970) is unlike Levelt's (1965a) model, in that he defines the weight of each monocular surface *explicitly* and independently of subjective brightness measures by taking into account the effects of differing amounts of contrast and contour in the two monocular views. In response to Engel's model, De Weert and Levelt's (1974) centroid model uses luminance to determine the weighting coefficients. However, they do not discuss the possible effects of contours, limiting their model's predictive power. Legge and Rubin's (1981) and Legge's (1984) data can be characterized as following a quadratic summation rule rather than a linear summation rule. While their formula assumes that the two monocular channels are equally sensitive, their equation can be altered to account for ocular dominance by weighting each monocular input.

The binocular summation and averaging models discussed so far do not address their anatomical location. However results obtained by Westendorf, Blake, Sloane, and Chambers (1982) suggest that the site of suppression follows the site of summation since suppression does not restrict binocular interactions (also see Blake & Overton, 1979). Westendorf et al. (1982) determined this by presenting a high contrast grating to one eye while the other eye

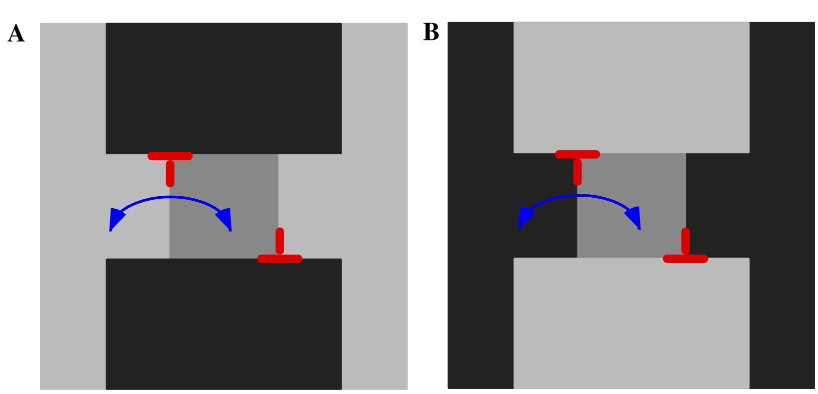


Fig. 2. Melfi and Schirillo's (2000) altered displays including T-junctions in red and maximum induction as a blue arrow, with either (A) a light region inducer or (B) a dark region inducer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

viewed a homogeneous field. This resulted in suppression; where the grating was seen continuously while the homogeneous field was suppressed. However, presenting identical images to each eye resulted in summation. These results suggest that the site of grating induction occurs before rivalry, and rivalry (i.e., suppression) occurs after summation, somewhere at, or beyond, striate cortex.

The literature on binocular fusion and rivalry states that summation or partial summation will occur when the monocular luminances are similar. Subtraction will occur when the monocular luminances are very different. However, Fechner's paradox (a form of subtraction, where binocular brightness judgments are *lower* than the more intense monocular input) will occur only when contours are present (Gregson, 1989). When contours are mismatched in the monocular images, rivalry may also occur in which pieces of the two monocular inputs will alternately appear. Given the importance of contours in binocular vision, it is paramount to understand the role of perceptual junctions in binocularly fused images.

1.3. Anatomical loci

In all of the models reviewed, it has been assumed that summation takes place at or beyond striate cortex, after combining the two eyes signals. However, the junction literature never states whether junctions are processed primarily in the retina or cortex, although they are often implicitly considered as cortical processes. This is because the properties of ON and OFF retinal ganglion cells seem insufficient to explain the complex grouping properties of junctions. One way to test the extent that T-junction computations occur in either the retina or the cortex is to present a T-junction that exists only in a fused state. If a binocularly fused T-junction has an effect beyond that of a monocular T-junction, the extent that it can be considered a cortical, and not retinal, process can be determined. Unfortunately, since the specific location of summation is unknown, it may be impossible to determine how high up in cortex T-junctions are processed.

Consequently, this paper will examine the likelihood that T-junction mechanisms influence brightness induction processes retinally and/or cortically. Cortical effects will be separated from retinal effects using binocular fusion. Stimuli will be created without T-junctions in either monocular image, only in the combined binocular percept. Measures of induction using these stimuli can be compared to those obtained using stimuli where T-junctions also exist in the monocular image.

2. General methods

2.1. Participants

The same 10 observers (four males) participated in each experiment. They all had normal or corrected-to-normal acuity and normal stereo vision (assessed using the Randot Stereotests published by the Stereo-Optical Co., Inc.). All were right-handed and right-eye dominant. All of the observers were inexperienced making brightness judgments and naive about the experimental paradigm. All procedures were approved by the Institutional Review Board of Wake Forest University and were performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

2.2. Stimuli

A Power Macintosh 7600/132 generated the images, which were presented on a Radius Pressview 17SR 17 in. color monitor. The 832 × 624 pixel screen produced achromatic stimuli at CIE chromaticity $x = .31$, $y = .32$. The scan rate of the monitor was 75 Hz noninterlaced. The monitor was viewed haploscopically at an optical distance of 122 cm in a dark room. The mirrors were adjustable so that observers always obtained a crisp fused percept. The left-hand side of the CRT projected an image to only the left eye while the right-hand side of the CRT screen projected an image to only the right eye.

The CRT screen simultaneously displayed four separate surrounds (e.g., the upper-right surround contained either a checkerboard (Figs. 1a and 3), or a single-region T-junction surround

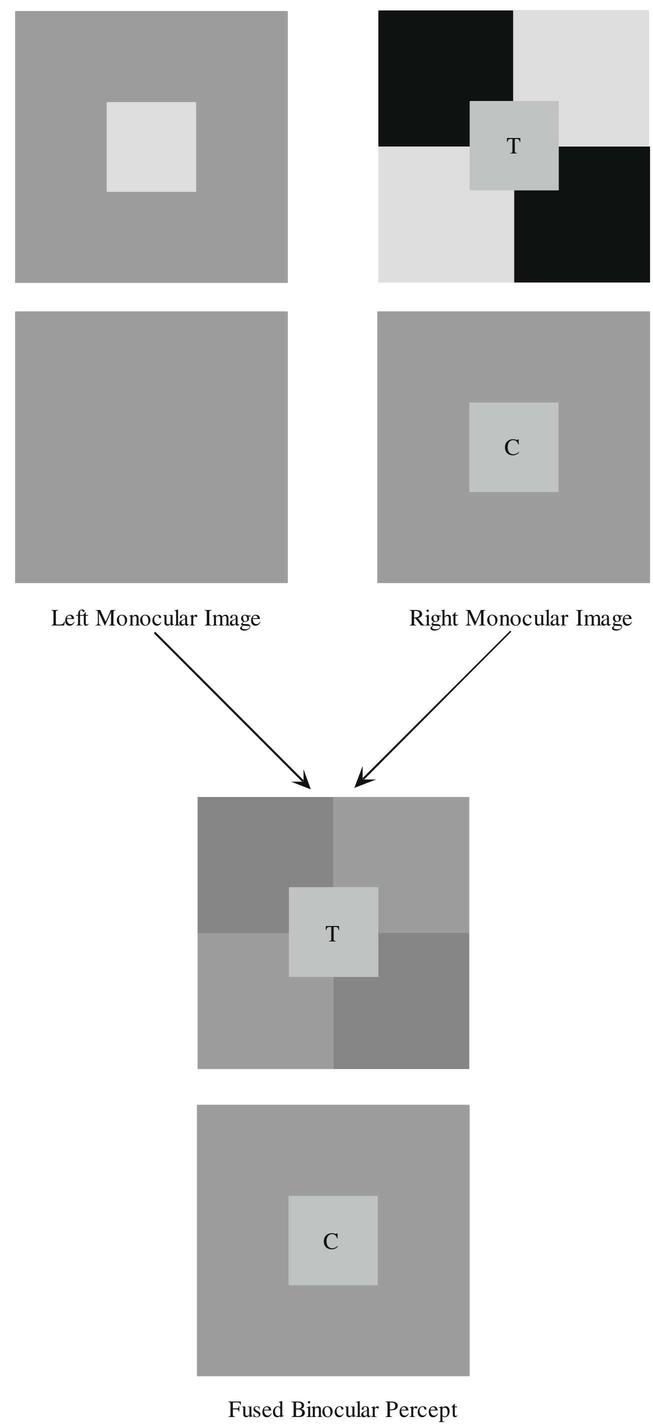


Fig. 3. Binocular control checkerboard stimuli shown as top four images, while the fused percept is indicated as the bottom two images.

(Fig. 2a and b). The surround was considered an incremental single-region T-junction surround if the surround region crossing the T-junction was lighter than the surround region abutting the top of the T-junction (Fig. 2a). The surround was considered a decremental single-region T-junction surround if the surround region crossing the T-junction was darker than the surround region abutting the top of the T-junction (Fig. 2b). Each surround was $4.5° \times 4.5°$. Haploscopic viewing caused the left and right surrounds to fuse and form a single binocular percept (e.g., Figs. 3–5). The two bottom monocular surrounds always had a luminance of 50 cd/m^2 and appeared uniform gray. In the checkerboard surround conditions, the checks were $2.25° \times 2.25°$ (e.g., Figs. 3 and 4). In the single-region T-junction surround conditions (Fig. 2), the inducing and non-inducing regions were equated in area to maintain the same space-average luminance as the checkerboard surround condition.

A $1.4° \times 1.4°$ comparison patch was always located in the center of one side of the bottom surround, and a $1.4° \times 1.4°$ test patch was always located in the center of the same side of the top surround. The luminance of the comparison patch was varied pseudo-randomly by the computer from trial to trial in 10% incre-

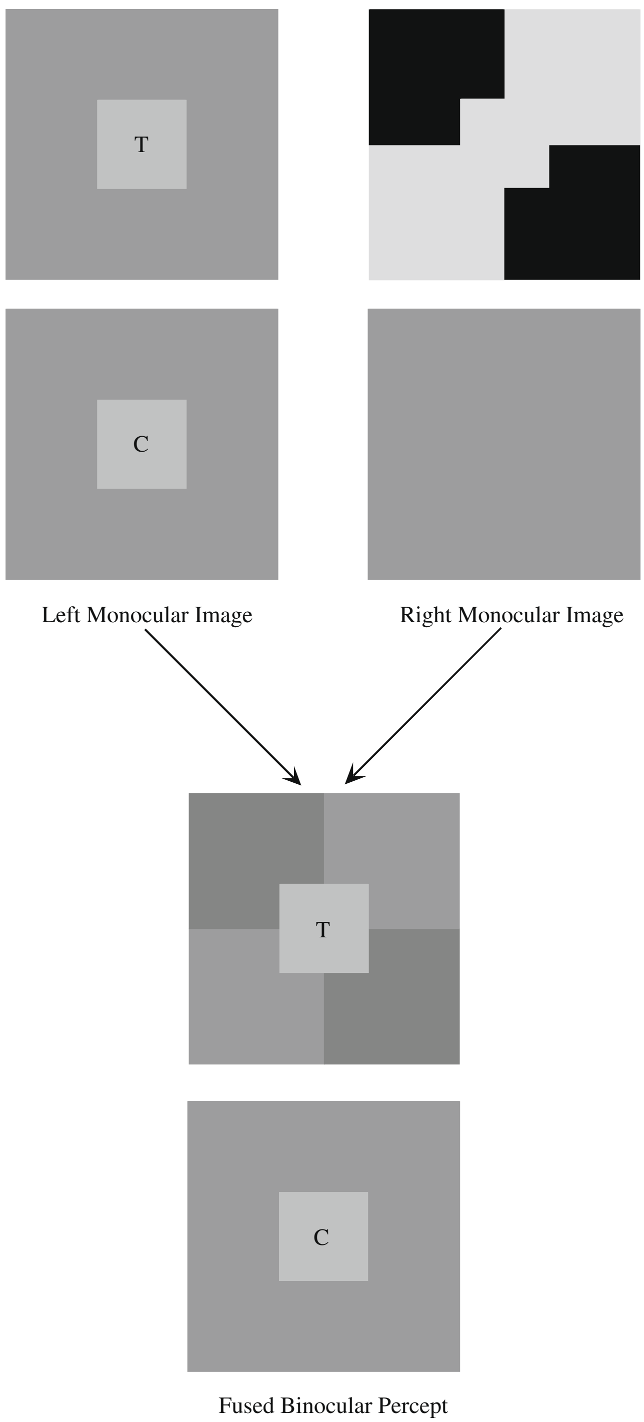


Fig. 4. Binocular fused checkerboard stimuli shown as top four images, while the fused percept is indicated as the bottom two images.

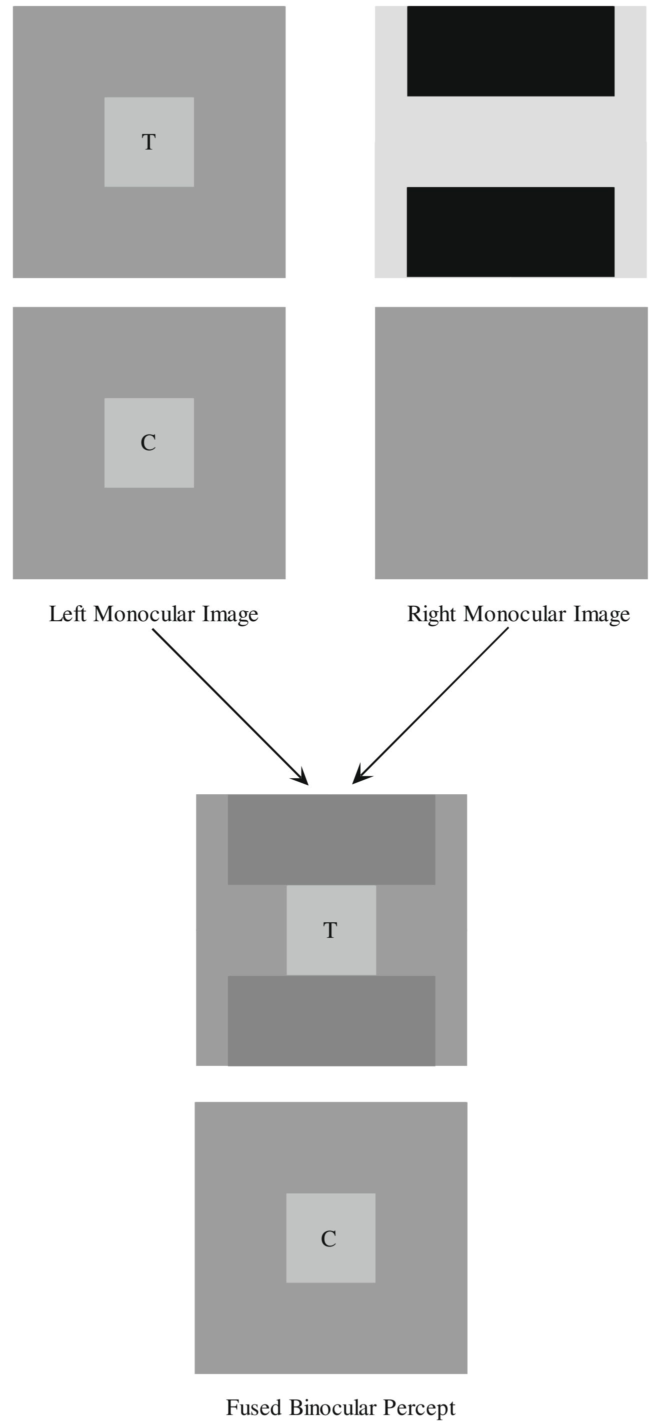


Fig. 5. Binocular fused single-region stimuli (light inducer) shown as top four images, while the fused percept is indicated as the bottom two images.

ments from 10% to 100%. In the center of both top and bottom surrounds of all experiments was a black central cross whose cross bars were .04° × .22°. The crosses added enough contour to promote fusion and prevent rivalry between the left and right images.

2.3. Procedure

The procedure was identical for all experiments unless otherwise noted. Observers maintained a stable head position with a chin rest. They dark-adapted for 3 min and then light-adapted for 3 min to a uniform field at the mean luminance level of the test- and comparison-surround luminance configurations that immediately followed. Observers adapted to each surround configuration for 5 min before making any brightness matches. After each brightness match, observers adapted for 30 s to the new comparison patch luminance level before making a brightness match. The adaptation time was chosen so that a stable fused image could be obtained. An experimental session consisted of pseudo-randomly presenting each comparison patch luminance level (luminance in 10% increments from 10% to 100%) at each surround contrast. Three repetitions of each condition were presented in a session. Each of the surround configurations was run in a separate experimental session. The mean and standard error of the means in the graphs are based on repeated measures individual means over three experimental sessions for 10 observers ($N = 10$).

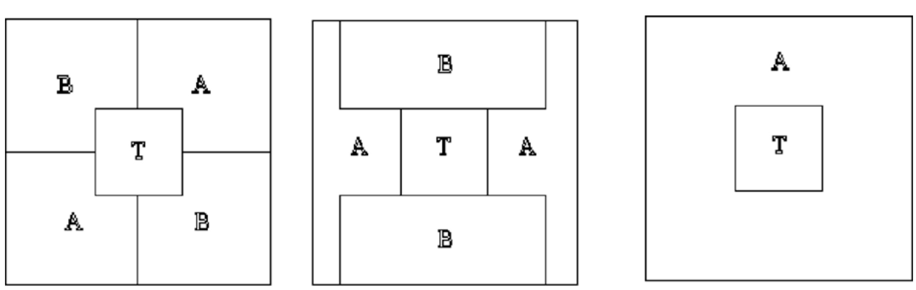
Observers used a method of adjustment to set the test patch intensity to appear identical to the comparison patch intensity. Observers varied the test patch luminance using a joystick. The up–down joystick direction varied the test luminance in steps that were ±4% of the luminance of the test value, while left–right movements varied the test luminance in steps that were ±0.33% of the luminance of the test value. A button at the base of the joystick signaled that a satisfactory match had been made, at which point the test luminance was recorded and the trial ended.

For all surround types and comparison patch luminance levels, 10 different surround conditions (a–j) where used, as shown in Fig. 6. Due to the extensive adaptation periods, it was impossible for some experimental sessions to contain the entire range of contrasts. In those cases, the range of contrasts was divided into two separate sessions, where each session contained either five or six surround contrasts. All sessions contained the 0% contrast surround, which allowed different conditions within each session to be normalized, and thus be directly comparable to one another. Each surround condition took about 30 min to complete. Each experimental session took between two and a half to three hours to complete, depending on whether five or six surround conditions were presented in an experimental session.

3. Experiment 1: binocular fusion

Melfi and Schirillo (2000) presented test and comparison stimuli side-by-side. With checkerboard surrounds (Fig. 1a) they showed that the lighter check induced darkness in increments, while symmetrical induction occurred with decrements. However, T-junction surrounds (Fig. 2b) made the dark surround regions lighten decrements. In the current experiments, a haploscope presented these stimuli, thereby linking Melfi and Schirillo's two-dimensional stimuli (2000) to binocularly fused stimuli. Instead of viewing the test and comparison surrounds by both eyes in a side-by-side presentation, the stimuli were viewed monocularly in a top-and-bottom arrangement. This set of experiments involved using either checkerboard surrounds (Fig. 1a), or an incremental single-region T-junction surround (Fig. 2a), or a decremental single-region T-junction surround (Fig. 2b), or uniform surrounds (not shown) whose luminance value equaled one of the checks (Fig. 6).

Experiment 1 involved restricting the junctions present in the various surrounds to cortical processes only. This was accomplished by locating the small square test and comparison patches on the two left-eye surrounds (Figs. 4 and 5). In this case, T-junctions are present only in the upper *fused* image. If the effects of T-junctions are entirely cortical, then Experiment 1 should have a comparable effect on grouping and induction as in control Experiments 2 and 3. This is because these control experiments also have T-junctions present in their right-eye monocular image (e.g., Fig. 3).



Surround Condition	Region A Luminance	Region B Luminance
a	98.4	1.6
b	86.3	13.7
c	74.2	25.8
d	62.1	37.9
e	50.0	50.0
f	41.74	58.26
g	33.47	66.53
h	25.21	74.79
i	16.94	83.06
j	8.68	91.32

Fig. 6. Schematic of the three surround types (i.e., checkerboard, single-region T-junction, and uniform). A and B refer to the luminances (in cd/m^2) in those regions for surround conditions a–j. In the binocular fused checkerboard (Fig. 4) and binocular fused single-region stimuli (Fig. 5) the test region (T) has the same luminance as region A.

3.1. Method

3.1.1. Participants

All 10 observers took part in the experiment.

3.1.2. Stimuli, design and procedure

The test and comparison patches appeared in the left monocular surrounds for the checkerboard surround condition (Fig. 4), the single-region T-junction surround condition (Fig. 5), and the uniform surround condition (not shown). For the stimuli represented in Fig. 4, the luminance of the central right-hand region was the same luminance as both the top-right check and bottom-left check. The luminance of this region in the single-region T-junction condition was the same as the inducing region luminance (Fig. 5). In the uniform surround condition, the luminance of the uniform right-hand test surround was identical to the luminance of the upper right-hand check in the checkerboard surround conditions (see Fig. 6). In all cases the luminance of the upper-left surround was the same as the bottom surrounds. Binocular rivalry at high contrasts limited the range of both the checkerboard and single-region T-junction experimental conditions. This limited range made it possible for all the available contrasts to be run in a single experimental session. All of the other procedures were identical to those described in the general method section.

3.2. Results

To eliminate possible adaptation effects and make the data comparable to Melfi and Schirillo (2000), all graphs were normalized by doing a multiplication with the ratio of the comparison and test luminances at the setting for equal surrounds. The normalization was between −6.6% and 7% produced by a normalization factor of between 0.934 and 1.07.

The results for the binocular uniform surround condition are shown in Fig. 7a. The x-axis represents the comparison patch luminance set by the experimenter, making comparison luminance values below 50 cd/m^2 decrements, and above 50 cd/m^2 increments. The y-axis represents the luminance the observer set the test patch to when matching a given comparison patch in brightness. The dashed line represents the theoretical identity matches, which are correct monocular matches, made on the uniform (i.e., 50 cd/m^2) test surround. Normalizing the data adjusted the matches

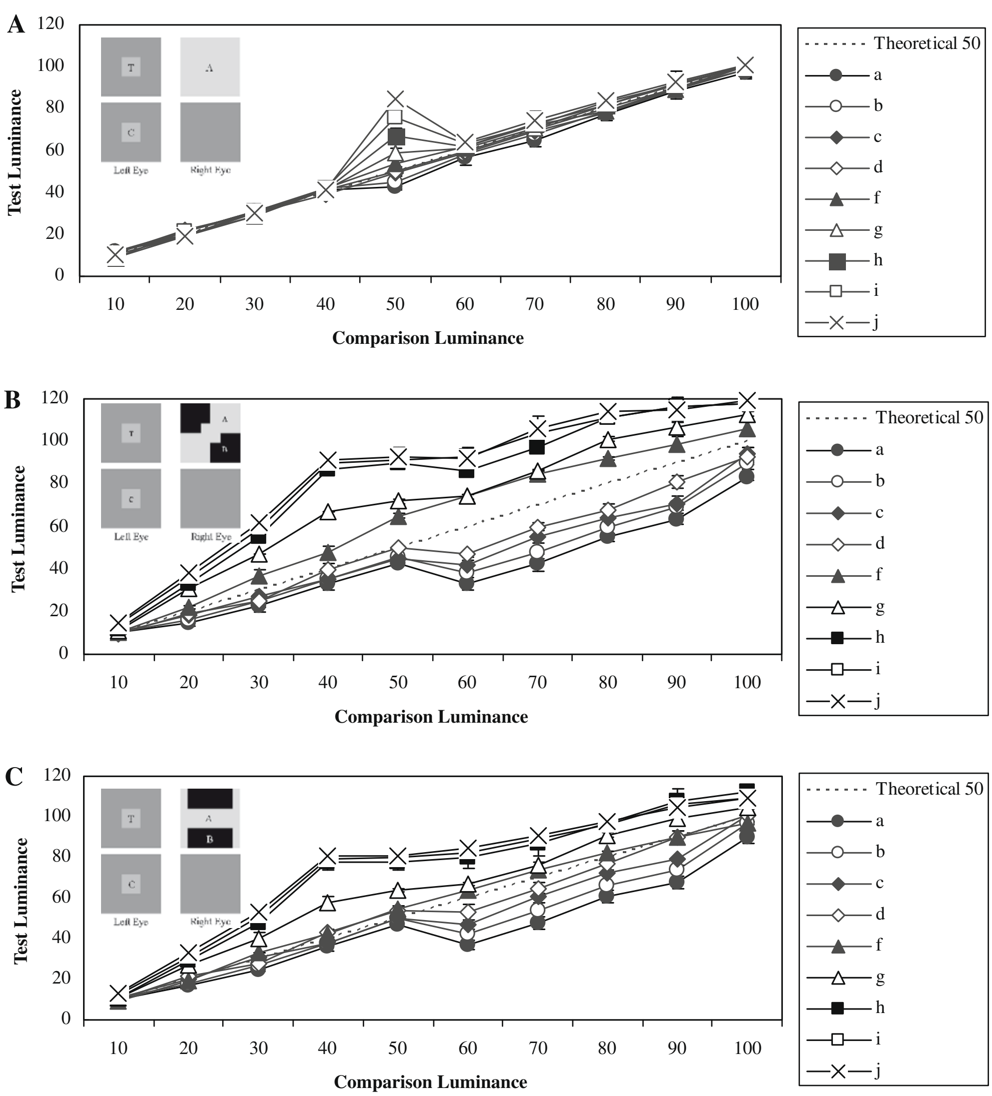


Fig. 7. Fused uniform, checkerboard and single-region surround results. Comparison luminance 10–40 are decrements, 60–100 are increments. Theoretical 50 is an equal luminance (dashed) line. (A) Uniform surround: a–d correspond to light test-surround luminance, f–j correspond to dark test-surround luminance. (B) Checkerboard surround: a–d correspond to light top-right and bottom-left check test-surround luminance, f–j correspond to dark top-right and bottom-left check test-surround luminance. (C) Single-region surround: a–d correspond to light test-surround inducer luminance, f–j correspond to dark test-surround inducer luminance. Error bars = SEM.

made on the uniform test surround (i.e., the 50 cd/m^2 background condition) to fit this line, and are therefore not shown.

Uniform surround fused decrement brightness matches were set very close to the theoretical equal luminance line (Fig. 7a). In contrast, uniform surround fused increment matches were more variable than decrement matches. Even so, it is noteworthy to have such a small vertical spread using surrounds that ranged from 8.68 cd/m^2 to 98.4 cd/m^2. When the comparison luminance was 50 cd/m^2, all observers deviated significantly in all surround conditions from the theoretical equal luminance line. That is, matches on test surrounds lighter than the comparison surround (see Fig. 6, symbols a–d) are set slightly below the theoretical equal luminance line while observers set matches significantly above the theoretical equal luminance line with test surrounds darker than the comparison surround (see Fig. 6, symbols f–j).

The results of the checkerboard fused surround and single-region fused surround conditions are shown in Fig. 7b and c, respectively. For the checkerboard fused surround condition, all observers set matches made on the f–j conditions (see Fig. 6) above the theoretical equal luminance line. The increment matches made on the a–d background conditions were set below the theoretical line, while decrements matched on these surround conditions more closely approximated the theoretical equal luminance line (Fig. 7b). The single-region surround condition shows a similar pattern of results as the checkerboard fused surround condition, except that the deviations away from the theoretical equal luminance line are significantly reduced (Fig. 7c).

Fig. 8a and b plots the percentage difference between the single-region fused surround condition and the checkerboard fused surround condition. That is,

$$\text{Percent Difference} = ((SR_F - check_F)/check_F) * 100 \quad (1)$$

where SR_F is the single-region fused surround condition and $check_F$ is the checkerboard fused surround condition. For light test-surround inducer luminances, observers (Fig. 8a) showed a 9.4% increase on average in the single-region surround condition over the checkerboard surround condition. For dark test-surround inducer luminances, observers (Fig. 8b) showed an 11.0% decrease on average in the single-region surround condition over the checkerboard surround condition.

3.3. Discussion

In the binocular fused uniform surround condition (Fig. 7a), observers could have simply used their left-eye to match the test and comparison patches in brightness. This would have produced an identity match that would correspond to the dashed 45-degree theoretical equal luminance line (see Fig. 7a). This seems to be nearly the case for decrements. However, for increments, the increase in variability around the theoretical equal luminance line suggests an influence of the right-eye image. This is evidence of an increment/decrement asymmetry. Also, when the comparison patch has a luminance of 50 cd/m^2 and the test surround is light, it darkens the test patch significantly more than a dark test surround lightens it.

As the surround condition increases from a to j, the region that corresponds to the test patch in the right-hand image is getting increasingly darker. Therefore, as the surround condition increases, observers add more luminance to the test patch to compensate for this darkening, indicating that some type of binocular averaging is occurring. Interestingly, for decrements seen on a checkerboard surround (Fig. 7b), observers' matches approximate the theoretical equal luminance line; but only when the corresponding right-hand

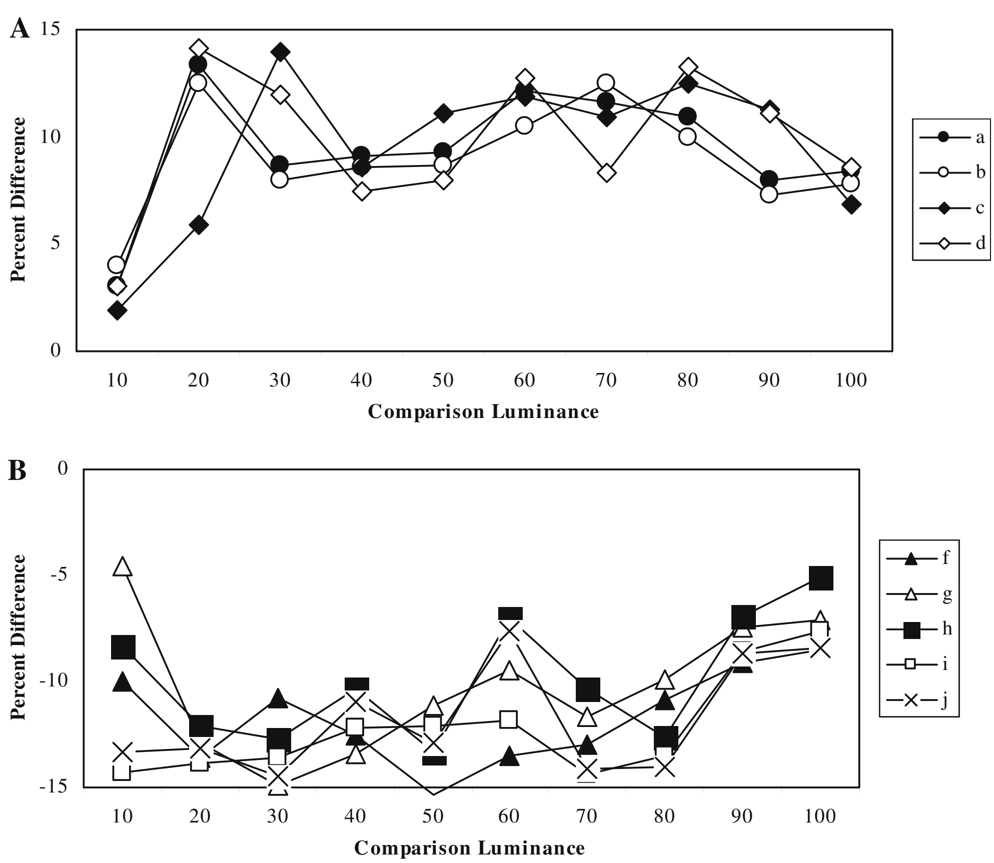


Fig. 8. Percent difference between fused single-region and fused checkerboard surrounds. Comparison luminance 10–40 are decrements, 60–100 are increments. (A) a–d correspond to light test-surround inducer luminance, (B) f–j correspond to dark test-surround inducer luminance.

test patch region was dark (i.e., had surround conditions a–d). The remaining data spread away from the theoretical equal luminance line in Fig. 7b. This may indicate the degree to which the right-hand checkerboard surrounds influenced the test patch, however, the brightness of the central region that was yoked to that of the upper-right and lower-left checks may also play a role. In contrast, in the single-region surround condition, the right-hand surrounds had much less of an effect (Fig. 7c) which can be seen as the data collapses toward the theoretical equal luminance line.

Fig. 8 emphasizes these findings by showing that the light inducer (Fig. 8a) dimmed both increments and decrements in the single-region surround condition compared to the checkerboard surround condition, while the dark inducer (Fig. 8b) brightened both increments and decrements for all observers. This suggests that the region in question is an inducing region which the T-junctions binocularly group with the test-patch.

4. Experiment 2: binocular control

Experiment 2 involved presenting the test- and comparison-patches within the right-eye monocular field, while having the two surrounds to the left-eye of the same space-average luminance as their right-eye surrounds (e.g., Fig. 3). In Experiments 1 and 2 the monocular images differ while the fused percepts are equivalent. Thus, if the results from Experiments 1 and 2 are comparable, it would suggest that the mechanisms that underlie induction as a result of T-junctions only require cortical processing.

4.1. Method

4.1.1. Participants

All 10 observers took part in the experiment.

4.1.2. Stimuli, design and procedure

The test and comparison patch appeared on the right monocular surrounds for the checkerboard surround condition (Fig. 3) and the single-region T-junction surround condition (not shown). Centered on the upper-left uniform test surround was a patch whose luminance was identical to the luminance of either the upper-right and lower-left checks in the checkerboard surround condition (Fig. 3) or the inducing check in the single-region T-junction surround condition (not shown). This was done to compare directly Experiments 1 and 2. The rest of the experimental parameters were identical to those described in the general method section.

As with Experiment 1, but unlike Experiment 3, binocular rivalry at high contrasts limited the range of both the checkerboard and single-region T-junction experimental conditions. This limited range made it possible for all the available contrasts to be run in a single experimental session. All of the other procedures were identical to those described in the general method section.

4.2. Results

In the checkerboard surround condition (Fig. 9a), all observers set brightness matches made on the f–h surround conditions (see Fig. 6) above the theoretical equal luminance line, while setting matches on the c–d surrounds below the theoretical equal luminance line. Decremental matches made on the c–d surrounds were not significantly darkened compared to increments. In the single-region surround condition (Fig. 9b) observers produced a similar pattern of results as in the checkerboard surround condition except the data had less spread.

Fig. 10a and b plots the percent difference between the single-region and checkerboard surrounds. That is,

$$\text{Percent Difference} = ((\text{SR}_{\text{BC}} - \text{check}_{\text{BC}})/\text{check}_{\text{BC}}) * 100 \quad (2)$$

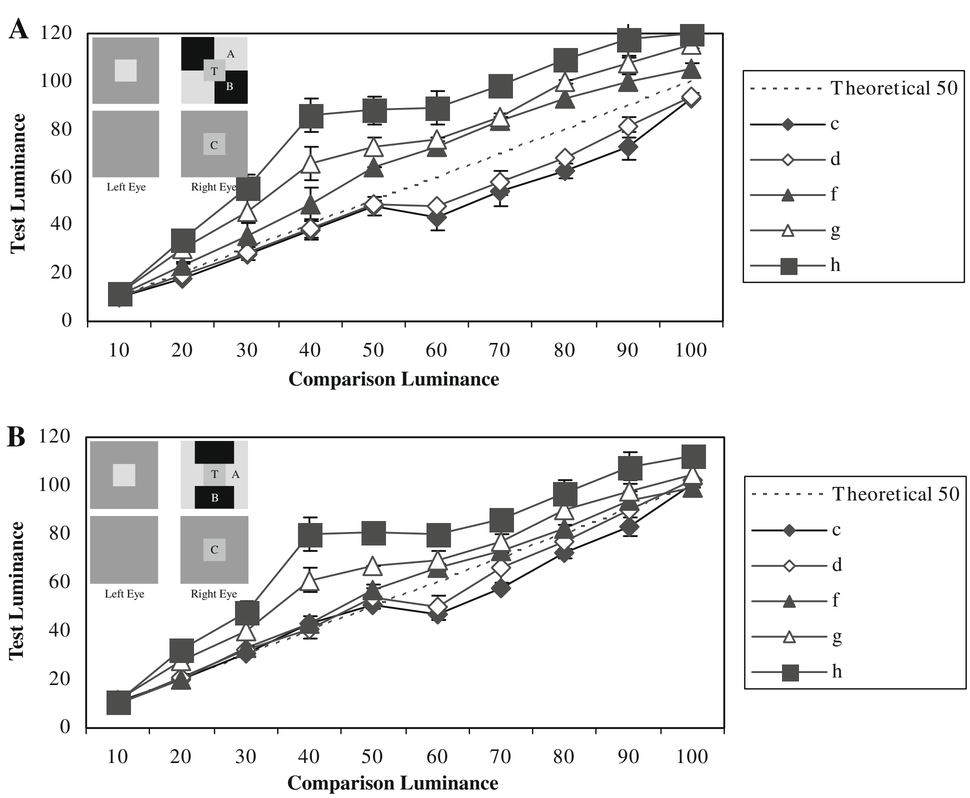


Fig. 9. Binocular checkerboard and single-region results. Comparison luminance 10–40 are decrements, 60–100 are increments. Theoretical 50 is an equal luminance (dashed) line. (A) Checkerboard surround: a–d correspond to light top-right and bottom-left test-surround luminance, f–j correspond to dark top-right and bottom-left test-surround luminance. (B) Single-region surround: a–d correspond to light test-surround inducer luminance, f–j correspond to dark test-surround inducer luminance. Error bars = SEM.

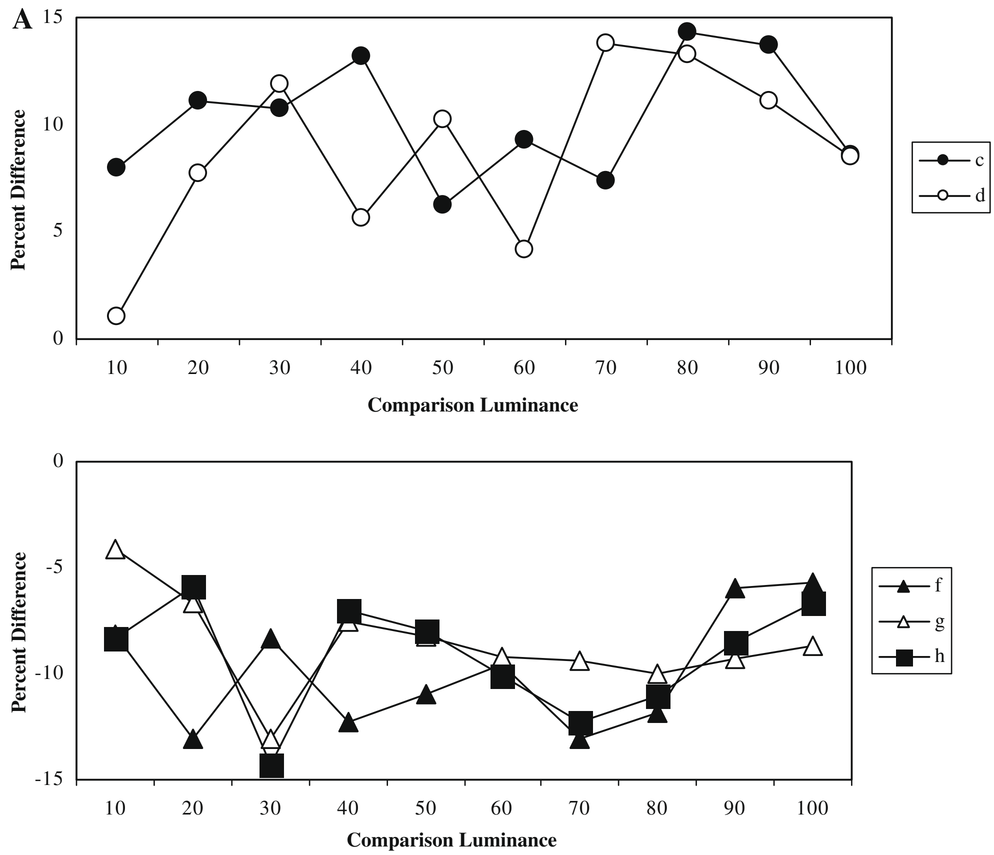


Fig. 10. Percent difference between binocular single-region and checkerboard surrounds. Comparison luminance 10–40 are decrements, 60–100 are increments. (A) c–d correspond to light test-surround inducer luminance, (B) f–h correspond to dark test-surround inducer luminance.

where SR_{BC} is the single-region binocular control surround condition and $check_{BC}$ is the checkerboard binocular control surround condition. For light region inducers (Fig. 10a) observers showed a 9.0% increase on average, while for dark region inducers (Fig. 10b) they showed a 9.5% decrease on average.

Fig. 11a and b shows difference plots between the binocular control checkerboard surrounds and the fused checkerboard surrounds. That is,

$$\text{Percent Difference} = ((\text{check}_F - \text{check}_{BC})/\text{check}_{BC}) * 100) \quad (3)$$

where $check_F$ is the checkerboard fused surround and $check_{BC}$ is the checkerboard binocular control surround. When the light check was on the top-right (see Fig. 6, c–d surrounds), observers (Fig. 11a) showed a statistically insignificant difference from zero (ANOVA $F(9,9) = 2.13$, $p = 0.14$) in the checkerboard fused surround condition compared to the checkerboard binocular control condition. When the dark check was on the top-right (see Fig. 6, f–h surrounds), observers (Fig. 11b) showed a statistically insignificant difference from zero (ANOVA $F(9,9) = 1.97$, $p = 0.16$) in the checkerboard fused surround condition compared to the checkerboard binocular control condition.

4.3. Discussion

As the surround condition increased from a to j, the left-hand test surround got increasingly darker (see Fig. 6). This was done to allow for direct comparisons to be made between the previous binocular fused and the current binocular control conditions. There were no significant differences between binocular fused and the current binocular control conditions (Fig. 11a and b), suggesting that T-junction inducing effects are comparable across monocular and binocular conditions.

Light regions enhance induction on the single-region surround condition compared to the checkerboard surround condition for all observers (Fig. 10a). This was predicted by Melfi and Schirillo (2000). Likewise, dark regions enhance the induction of decrements on the single-region surround condition compared to the checkerboard surround condition for all observers (Fig. 10b).

5. Experiment 3: monocular replication

Melfi and Schirillo (2000) presented test and comparison stimuli side-by-side. Instead of viewing the test and comparison surrounds by both eyes in a side-by-side presentation, the stimuli in control Experiment 3 were viewed monocularly in a top-and-bottom arrangement. This experiment is comparable to that of Melfi and Schirillo (2000). In the present experiment the display is viewed with one eye instead of two, but there is little reason to assume that this difference will influence the results substantially.

5.1. Method

5.1.1. Participants

All 10 observers took part in the experiment.

5.1.2. Stimuli, design and procedure

The test and comparison patch appeared on the right monocular surrounds for the checkerboard surround condition (Fig. 1a shows upper test patch and surround), the single-region T-junction sur-

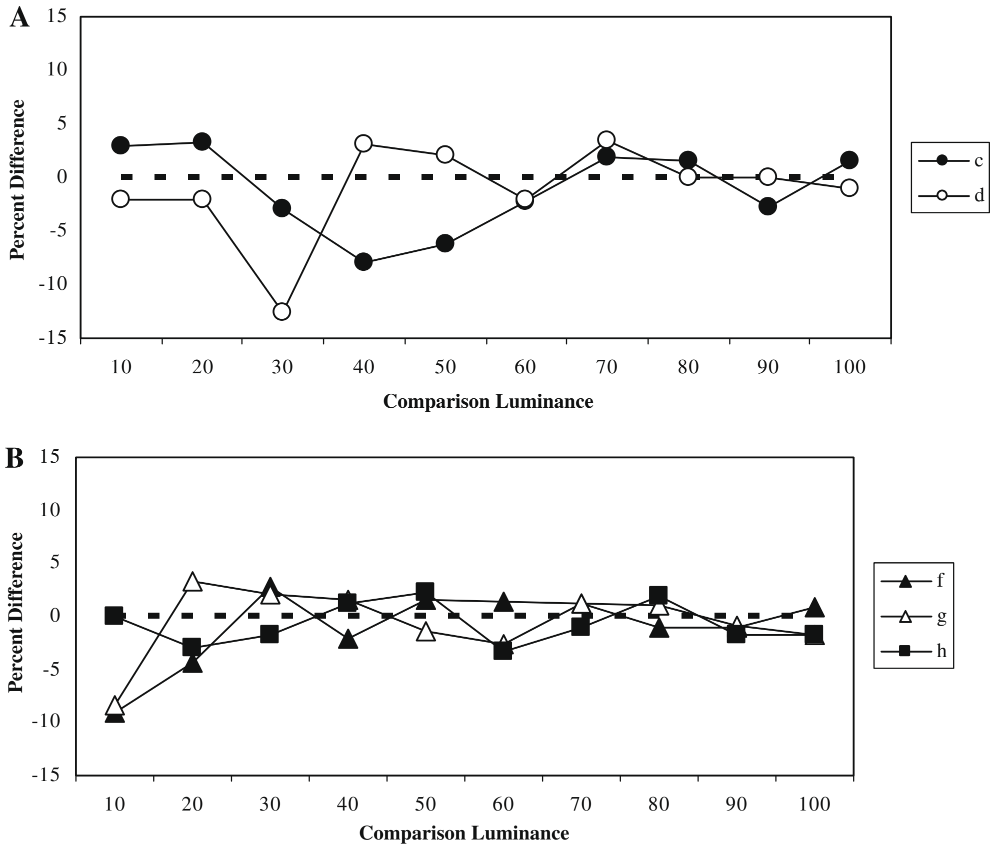


Fig. 11. Percent difference between fused checkerboard surround and binocular control checkerboard surround. Comparison luminance 10–20 are decrements, 60–100 are increments. (A) c–d correspond to light test-surround inducer luminance, (B) f–h correspond to dark test-surround inducer luminance.

round condition (Fig. 2a and b shows upper test patch and surround), and the uniform surround condition (not shown). The rest of the stimulus parameters were identical to those described in the general method section.

The left side of the screen was covered completely with a 27 cm × 42 cm piece of black felt and the observers' left eye was also patched. That is, even though a haploscopic set-up was used only the right half of the screen was visible. All of the other procedures were identical to those described in the general method section.

5.2. Results

The results from the uniform surround monocular condition are shown in Fig. 12a. On average, Fig. 12a indicates that when the test surround was lighter than the comparison surround (i.e., test surround conditions a–d, see Fig. 6), matches were set above the theoretical equal luminance line. However, when the test surround was darker than the comparison surround (i.e., test surround conditions f–j, see Fig. 6), the matches were not set as far below the theoretical equal luminance line. Moreover, test patch decrements were more closely matched to the comparison patch when the comparison patch luminance equaled its own surround. However, test patch increments appeared somewhat too dark and had to be lightened slightly.

Fig. 12b and c plots the monocular checkerboard and monocular single-region T-junction surround data, respectively. Decrements on the checkerboard surround and single-region T-junction surround cluster around the theoretical equal luminance line, although there is slightly more spread in the single-region T-junction surround data. Increments on the checkerboard surround and single-region T-junction surround are mostly shifted above the theoretical equal luminance line, indicating that most test patches appeared too dark and had to be lightened to match a comparable comparison patch. This effect is amplified in the single-region monocular surround condition.

Fig. 13a and b plots the percentage difference between the test luminances set on the two inhomogeneous surrounds. That is,

$$\text{Percent Difference} = ((\text{SR}_{\text{MON}} - \text{check}_{\text{MON}})/\text{check}_{\text{MON}}) * 100 \quad (4)$$

where SR_{MON} is the single-region monocular surround and $\text{check}_{\text{MON}}$ is the checkerboard monocular surround. Since the raw data had been normalized, the percent change for the uniform fifty surrounds is always zero, and therefore are not shown.

When the lighter region crossed the T-junction (Fig. 13a) observers showed a 5.5% increase on average in the single-region surround condition compared to the checkerboard surround condition for decrements (i.e., comparison patch luminances of 10–40) and a 7.8% on average increase for increments (i.e., comparison patch luminances of 60–100). This suggests that the lighter region was an inducer. These increases were strongest at the smallest comparison patch increments/decrements and decreased as the comparison patch increments/decrements became larger. In contrast, when the darker region crossed the T-junction (Fig. 13b) observers showed a 10.0% decrease on average in the single-region surround condition compared to the checkerboard surround condition for decrements (i.e., comparison patch luminances of 10–40) and a 3.9% on average decrease for increments (i.e., comparison patch luminances of 60–100). This suggests that the darker region was an inducer. Again, these increases were strongest at the smallest comparison patch increments/decrements and decreased as the comparison patch increments/decrements became larger.

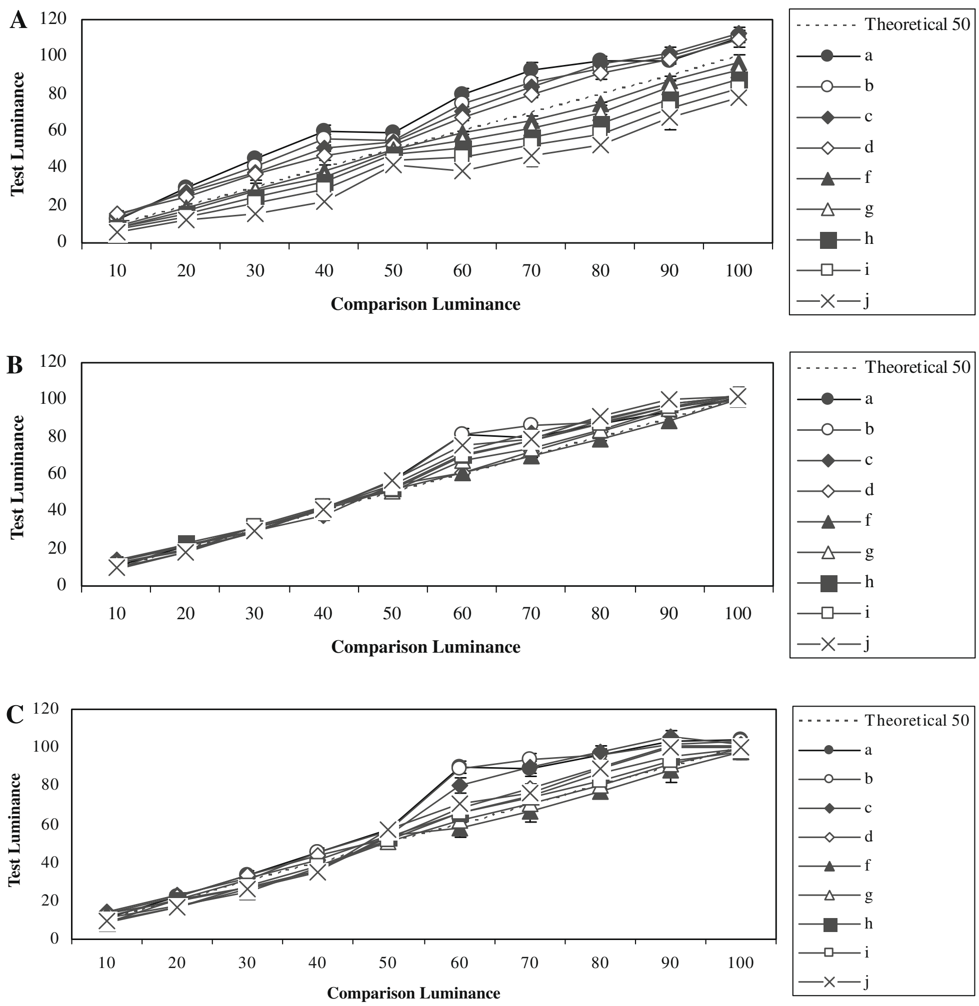


Fig. 12. Monocular uniform, checkerboard and single-region surround results. Comparison luminance 10–40 are decrements, 60–100 are increments. Theoretical 50 is an equal luminance (dashed) line. (A) Monocular uniform surround: a–d correspond to light test-surround luminance, f–j correspond to dark test-surround luminance. (B) Monocular checkerboard surround: a–d correspond to light top-right and bottom-left check test-surround luminance, f–j correspond to dark top-right and bottom-left check test-surround luminance. (C) Monocular single-region surround: a–d correspond to light test-surround inducer luminance, f–j correspond to dark test-surround inducer luminance. Error bars = SEM.

Fig. 14a and b plots the percent difference in the single-region fused versus the single-region control surround conditions. That is,

$$\text{Percent Difference} = ((SR_F - SR_{BC})/SR_{BC}) * 100 \quad (5)$$

where SR_F is the single-region fused surround condition and SR_{BC} is the single-region binocular control condition. When the light region was the inducer (see Fig. 6), observers (Fig. 14a) showed a statistically insignificant difference from zero (ANOVA $F(9, 9) = 2.25$, $p = 0.12$) in the single-region fused surround condition compared to the single-region binocular control condition. When the dark region was the inducer (see Fig. 6), observers (Fig. 14b) showed a statistically insignificant difference from zero (ANOVA $F(9, 9) = 2.11$, $p = 0.14$) in the single-region fused surround condition compared to the single-region binocular control condition.

5.3. Discussion

Fig. 12a suggests that the effect of induction on increments and decrements was slightly asymmetrical. For example, when the test surround was an increment (e.g., d – open diamonds, see Fig. 6), they set the test patch luminance significantly higher than the theoretical dashed line compared to when the test surround was a decrement of roughly the same magnitude (e.g., f – closed triangle, see Fig. 6).

Decrements on a monocular checkerboard surround are near identity matches (Fig. 12b) as predicted by Melfi and Schirillo (2000). While small increments appear darker as predicted (i.e., observers set the test above the theoretical equal luminance line), this effect is reduced with large increments.

The effects of T-junctions in the single-region condition are made evident in the difference plots in Fig. 13. With the light region inducers (Fig. 13a), there was a greater increase in darkness for increments than decrements in the single-region condition compared to the checkerboard condition. This replicates an important finding in Melfi and Schirillo (2000). Likewise, the dark regions make decrements appear brighter than increments in the single-region condition (Fig. 13b). These effects were largest with just barely perceptible increments/decrements, similar to von Bezold's (1874) discovery of 'crispening' (Semmelroth, 1970; Takasaki, 1966, 1967; Whittle, 1992). As predicted by Melfi and Schirillo (2000) these asymmetries suggest that a light (dark) inducer has a greater effect on increments (decrements) when surfaces edges have a T-junction present to enhance grouping.

More importantly, there was roughly equivalent induction in the single-region binocularly fused surround condition as in the

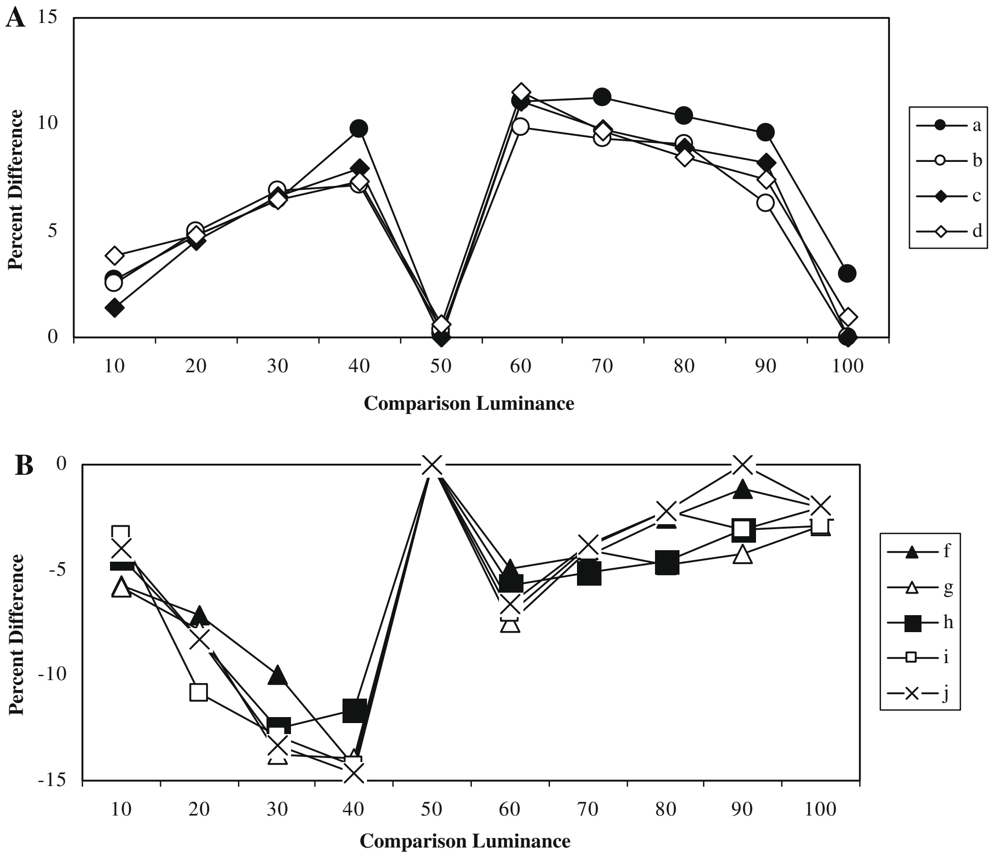


Fig. 13. Percent difference between monocular single-region and checkerboard surrounds. Comparison luminance 10–40 are decrements, 60–100 are increments. (A) a–d correspond to light test-surround inducer luminance, (B) f–j correspond to dark test-surround inducer luminance.

single-region binocular control surround condition (Fig. 14a and b). This indicates that in the single-region conditions, the presence of retinal and cortical or just cortical T-junctions made little difference on the amount of induction they produced.

Lastly, in control Experiment 2 light regions enhance induction on the single-region surround condition compared to the checkerboard surround condition for all observers (Fig. 10a). This was predicted by Melfi and Schirillo (2000) and is consistent with comparable monocular conditions (Fig. 8a). Likewise, dark regions enhance the induction of decrements on the single-region surround condition compared to the checkerboard surround condition for all observers (Fig. 10b) as consistent with comparable monocular conditions (Fig. 8b). Thus, the binocular fused experiment is as good a replication of the original study by Melfi and Schirillo (2000), if not better, than the monocular condition used in Experiment 3.

6. General discussion

6.1. T-junctions are processed cortically

Determining where in the visual system T-junctions are analyzed was accomplished by presenting the checkerboard surround conditions and single-region surround conditions so that a T-junction existed only in the binocular fused condition but not in either monocular image (Experiment 1; Figs. 4 and 5). The results suggest that T-junctions are processed cortically, after the point of fusion. This is clearly indicated by the enhanced induction present in the single-region surround condition compared to the checkerboard surround condition (Fig. 8a and b). This is the same pattern of results found in Experiments 2, 3, and Melfi and Schirillo (2000), where T-junctions were processed retinally and then cortically.

The monocular checkerboard data (Fig. 12b) are very different than both the checkerboard binocular control data (Fig. 9a) and the checkerboard fused data (Fig. 7b). That is, with the monocular checkerboard displays, decrements remain close to the theoretical equal luminance line while increments appear darker due to induction from the light checks. In contrast, in both the checkerboard binocular control and checkerboard fused displays, decrements as well as increments show strong induction. It is hypothesized that this is due to having different contrast surrounds in *both* eyes (see Figs. 4 and 5), while in the monocular checkerboard condition only one eye had surround contrast.

Always having contrast in the right-eye image may allow for processing of an ON-center increment signal while suppressing an OFF-center decrement signal. In conditions when a contrast signal is also present in the left-hand monocular input (i.e., the fused conditions), an OFF-center decrement signal is made available to the left-eye. This parsing of monocular signals into ON- and OFF-pathways allows for both increments and decrements to influence induction in the fused condition. T-junctions can then modify the fused monocular inputs. Thus, in the checkerboard condition only the light regions group with increments, while the dark regions do not group with decrements. However, in the T-junction conditions the decremental signal is released from suppression and dark regions group with decrements.

Without T-junctions to signal grouping and occlusion, as in the checkerboard surround conditions, monocular inputs simply combine and summation occurs. However, if there are T-junctions in the image whose regions signal grouping with the test, then those regions can modify how the monocular energies are summed to-

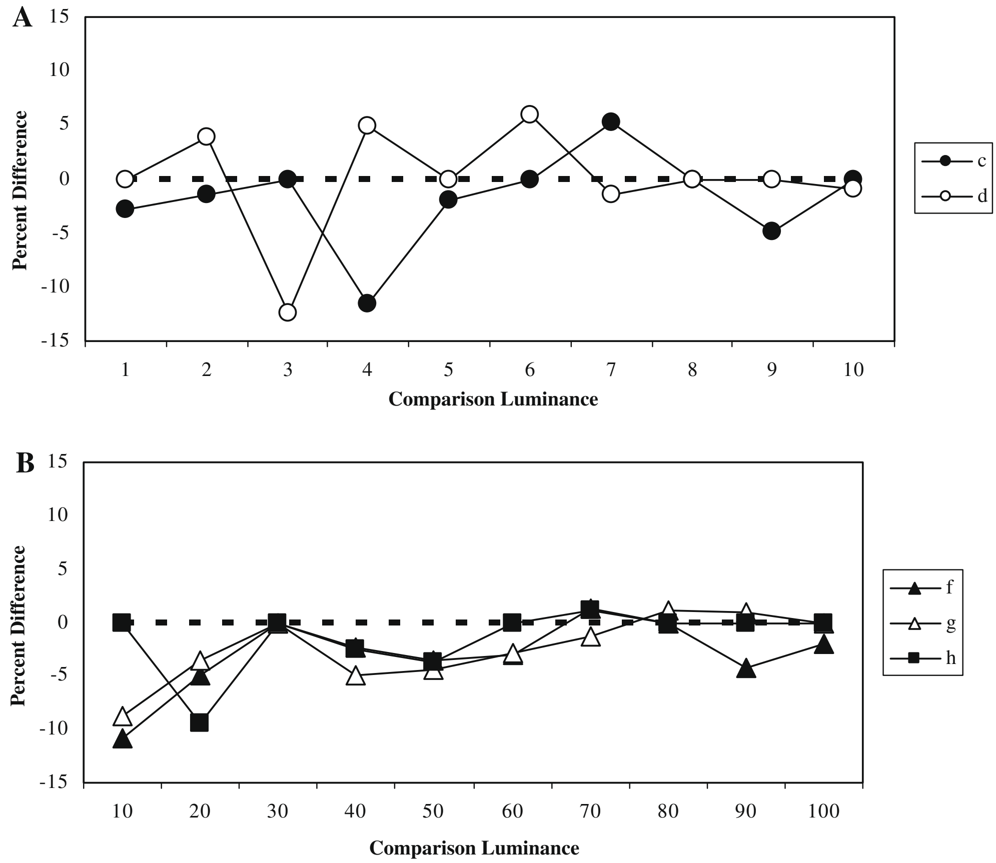


Fig. 14. Percent difference between fused single-region surround and binocular control single-region surround. Comparison luminance 10–20 are decrements, 60–100 are increments. (A) c–d correspond to light test-surround inducer luminance, (B) f–h correspond to dark test-surround inducer luminance.

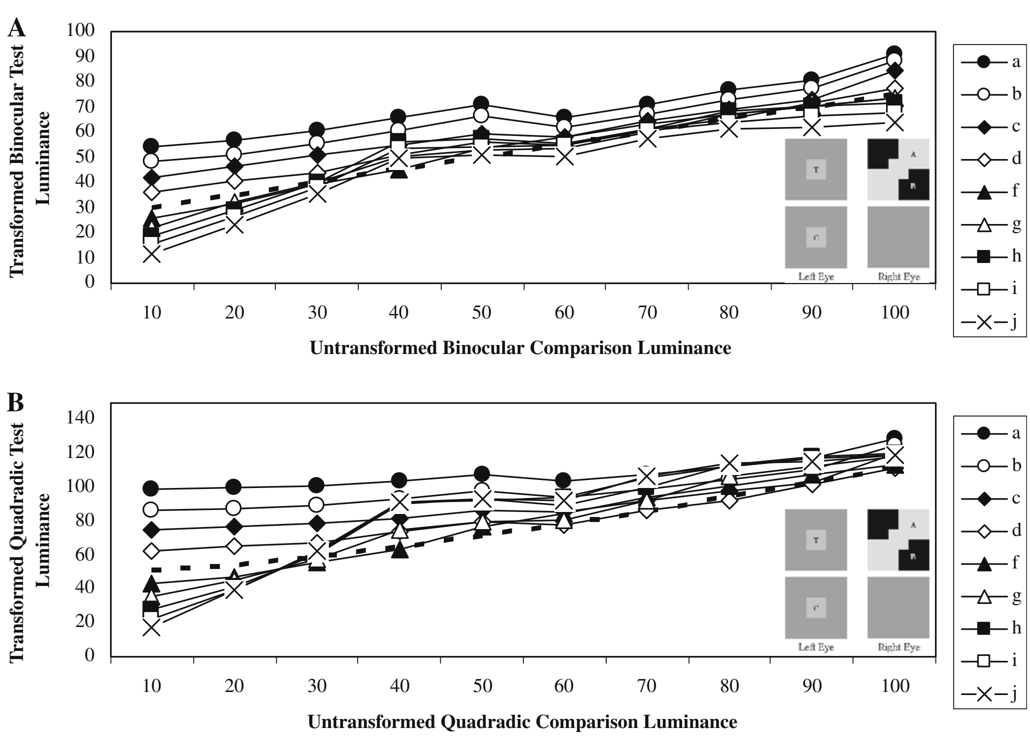


Fig. 15. Checkerboard surround results, where the transformed test checkerboard luminance is a function of untransformed comparison luminance. (A) Binocularly averaged, (B) quadratically averaged. a–d correspond to light test-surround check luminance, f–j correspond to dark test-surround check luminance. Dashed line corresponds to theoretical (A) averaging and (B) quadratic line.

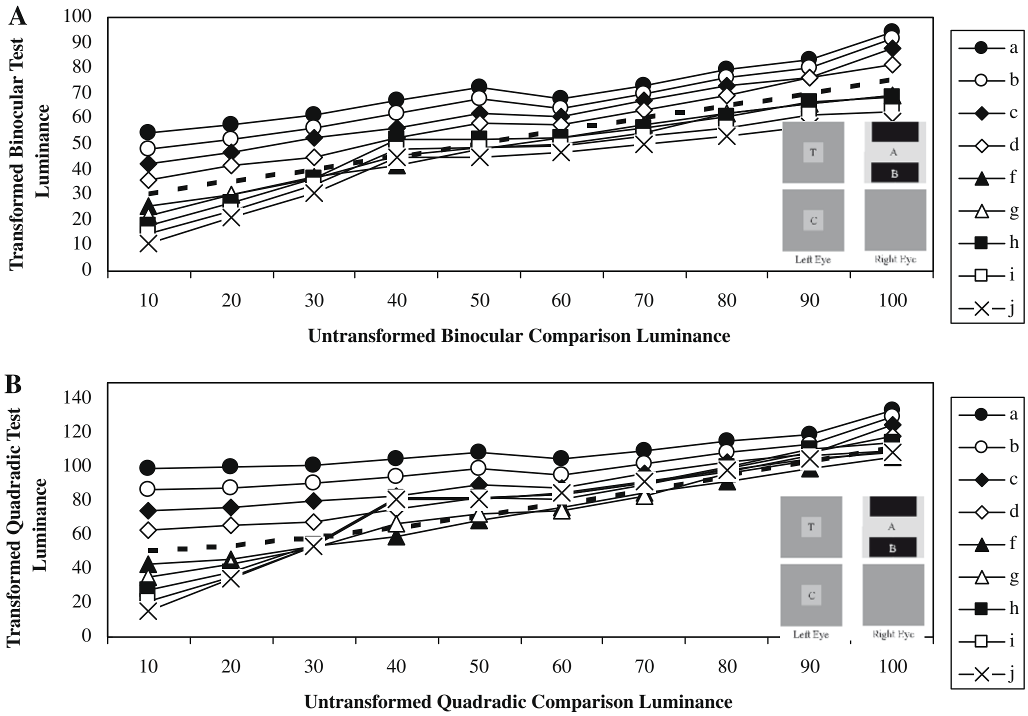


Fig. 16. Single-region surround results, where the transformed test single-region luminance is a function of untransformed comparison luminance. (A) Binocularly averaged, (B) quadratically averaged. a–d correspond to light test-surround inducer luminance, f–j correspond to dark test-surround inducer luminance. Dashed line corresponds to theoretical (A) averaging and (B) quadratic line.

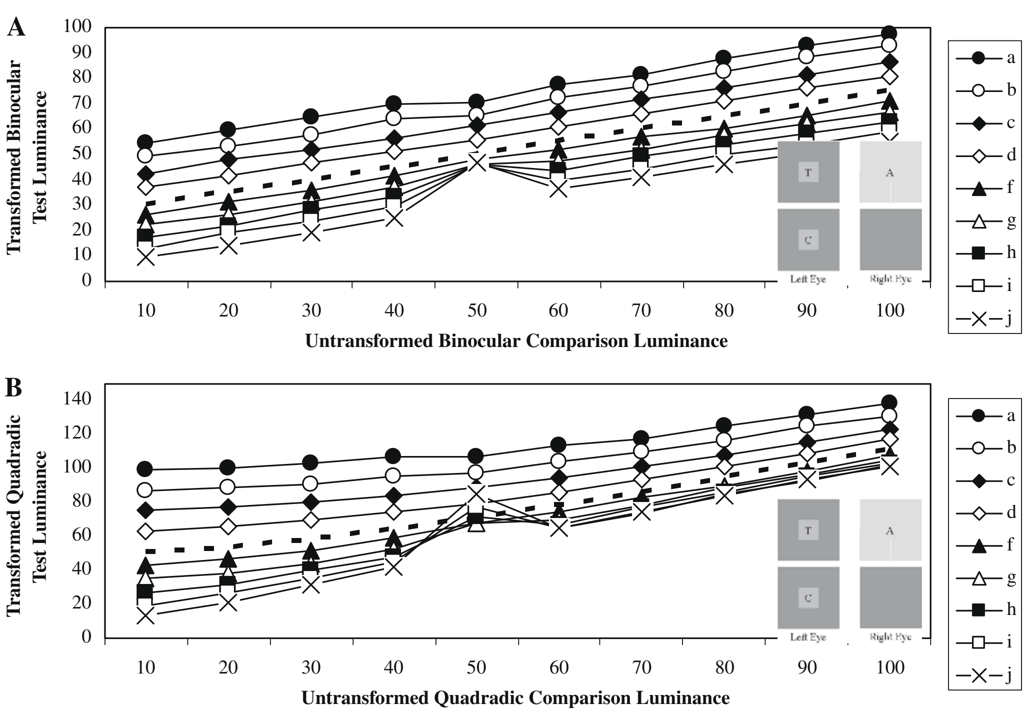


Fig. 17. Fused uniform, surround results, where the transformed test uniform luminance is a function of untransformed comparison luminance. (A) Binocularly averaged, (B) quadratically averaged. a–d correspond to light test-surround inducer luminance, f–j correspond to dark test-surround inducer luminance. Dashed line corresponds to theoretical (A) averaging and (B) quadratic line.

gether. This is shown as the reduction towards the equal luminance line from the checkerboard surround data to the single-region surround data (compare Fig. 7b and c).

6.2. Fusion

To examine binocular averaging from Experiment 1 the test patch luminance was transformed for any given match using the following equation:

$$L' = (L(X_t) + L(Y_t))/2 \quad (6)$$

where L' is binocularly averaged luminance, $L(X_t)$ is the monocular luminance of the test and $L(Y_t)$ is the monocular luminance of the corresponding contralateral region (see Fig. 6). To assess the degree to which the data approximate summation, theoretical averaging lines have been added to Figs. 15–17. The theoretical averaging line was obtained using

$$L'' = L(X_c) + L(Y_c))/2 \quad (7)$$

which is independent of the settings and conditions, so that L'' is theoretical averaged luminance, $L(X_c)$ is the monocular luminance of the comparison and $L(Y_c)$ is constant. This was done to see how well the data can be accounted for in terms of binocular averaging alone. Fig. 15a illustrates that observer's checkerboard fused data dramatically fail to average.

Another possible summation strategy is that the monocular luminance energies are combined quadratically (Legge, 1984). The quadratic transformation can be written as:

$$\text{Transformed Quadratic} = L''' = \sqrt{(L_l)^2 + (L_r)^2} \quad (8)$$

where L_l is the left-hand test or comparison patch luminance and L_r is the right-hand test or comparison region luminance. As with binocular averaging, the test and comparison patch luminances were quadratically transformed and a quadratic theoretical line is plotted in Figs. 15b and 16b. Neither the quadratic transformed checkerboard fused data (Fig. 15b) nor the quadratic transformed single-region fuse data (Fig. 16b) from Experiment 1 average.

One possible explanation why these results fail to average is that each eye's monocular contours differ affecting how each image is weighted. For example, in the uniform surround condition (Fig. 17a), when the contour strength is the same for both eyes, the data are grossly incompatible with binocular averaging. This is consistent with findings from Whittle and Challands (1969), who also found very little binocular averaging under rather similar conditions. Moreover, plotting the uniform surround fused data as an average (Fig. 17a) did not produce a better fit to plotting it as a quadratic (Fig. 17b).

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