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The effect of spatial layout on motion segmentation

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ABSTRACT

We present a series of experiments exploring the effect of the stimulus spatial configuration on speed discrimination and two different types of segmentation, for random dot patterns. In the first experiment, we find that parsing the image produces a decrease of speed discrimination thresholds such as was first shown by Verghese and Stone [Verghese, P., & Stone, L. (1997). Spatial layout affects speed discrimination threshold. *Vision Research, 37*(4), 397–406; Verghese, P., & Stone, L. S. (1996). Perceived visual speed constrained by image segmentation. *Nature, 381*, 161–163] for sinusoidal gratings. In the second experiment, we study how the spatial configuration affects the ability of a subject in localizing an illusory contour defined by two surfaces with different speeds. Results show that the speed difference necessary to localize the contour decreases as the stimulus patches are separated. The third experiment involves transparency. Our results show a little or null effect for this condition. We explain the first and second experiment in the framework of the model of Bravo and Watamaniuk [Bravo, M., & Watamaniuk, S. (1995). Evidence for two speed signals: a coarse local signal for segregation and a precise global signal for discrimination. *Vision Research, 35*(12), 1691–1697] who proposed that motion computation consists in, at least, two stages: a first computation of coarse local speeds followed by an integration stage. We propose that the more precise estimate of speed obtained from the integration stage is used to produce a new refined segmentation of the image perhaps, through a feedback loop. Our data suggest that this third stage would not apply to the processing of transparency.

1. Introduction

The extraction of motion information from visual scenes is one of the most important tasks that the human visual system needs to perform. At present, we do not know exactly how the visual system derives motion information from images projected onto the retina, but there are a large amount of psychophysical and physiological evidence that allow us to hypothesize that motion computation begins with the estimation of local parameters of the moving stimulus (Adelson & Bergen, 1985; Ascher & Grzywacz, 2000; McKee, 1981; Van Santen & Sperling, 1985; Watson & Turano, 1995). Because these local parameters may be ambiguous and affected by noise (Adelson & Movshon, 1982), local information needs to be integrated to produce a more robust representation of the global scene. Several authors showed evidence supporting this hypothesis (Braddick & Qian, 2001; Croner & Albright, 1999; De Valois & De Valois, 1990).

Motion may be a rich source of information for a variety of tasks including segmentation (Britten, 1999; Masson, Mestre, & Stone, 1999). This capability implies that the system can integrate local speed information within delimited boundaries of the visual field, i.e. the system integrates the speed information belonging to the same object. But, what is first in motion processing: segmentation or integration? The question seems hard to be answered because, if there are only local speed cues, the visual system needs to integrate the motion signal in order to disambiguate them, but before the integration the system needs to know which speeds belong to each object. Bravo and Watamaniuk (1995) approached this issue and collected evidence supporting the idea that the visual system computes speed twice: the first calculation produces a coarse local speed signal which is used to segregate objects; the second calculation integrates (temporal and spatially) these coarse speed signals in order to obtain precise velocity estimation for each object.

Although the authors suggest a temporal order for these computations, other authors (Yuille & Grzywacz, 1998) propose that there is an interaction between segregation and integration, which would imply that any of these processes could affect the other. Related to this, Verghese and Stone (1996, 1997) reported interesting results involving segregation and integration processes. They showed that increasing the area of a single signal patch has no effect on the speed discrimination threshold. However, when the number of signal patches (or the distance among them) is increased, the thresholds are lowered. Their data show that, for the

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worst spatial configuration, a subject needs speed increments 50% larger (average) than those needed for the best configuration, to discriminate between two speeds. They argued that thresholds improve for the multiple patches layout because the visual system has access to many independent samples of a noisy signal, which reduces the variance of the speed estimation.

Therefore, it is reasonable to hypothesize that if the precision in the estimate of speed depends on the spatial layout, the performance of other tasks in which speed is involved will be also affected by changes in the spatial configuration. In this paper, we investigate the particular case of segmentation. First, we tested whether the spatial effect on speed discrimination thresholds found by Verghese and Stone (1996, 1997) for sinusoidal gratings appears in random dots patterns. Second, we tested whether the spatial arrangement affects two different segmentation tasks: position discrimination of contours defined by the differences in speed of two adjacent surfaces, and transparency discrimination.

2. Experiment 1: speed discrimination vs. spatial arrangement

2.1. Methods

This experiment was designed to test whether the effect of the spatial layout on speed discrimination appears when random dots patterns are used as stimulus. We follow the Verghese and Stone (1997) fusion paradigm to perform the experiment. Only those configurations that keep constant both eccentricity and area were used. In the two cases in which patches appeared separately, they were circular, subtended a visual angle of 2.5°, and were located 4° away from the center of the screen. In the third configuration (fused) the three patches were fused to form a single banana-shaped patch whose total area was three times the area of a single circular patch. Thus, the angular distances between patches for each condition were: ∼12.5° (fused), 40° and 120°. We define the rotational position of the stimulus as the angle between the horizontal and a line linking the center of the screen and the center of a patch. The patches contained 40 square dots of 4 × 4 pixels (0.12° × 0.12° of visual angle), which were randomly positioned into the patch (see Fig. 1). All dots moved horizontally at the same speed and direction (left or right), which was randomized on trial. Stimulus patterns were created in MATLAB with the Psychophysics Toolbox (Brainard, 1997) and Video Toolbox (Pelli, 1997), and displayed on a calibrated monitor (1024 × 768 pixels resolution, 60 Hz). A subpixel motion procedure (Georgeson, Freeman, & Scott-Samuel, 1996) was used to produce small speed differences in our stimuli. Because the dots had not finite lifetime, they could escape from the patch. When this occurred, the dot was wrapped around. We used white dots (72 cd/m^2) over a black background (0.5 cd/m^2). To minimize the tendency to glance toward the stimuli that suddenly appear in the field of vision, and/or the tendency to track the dots, the subjects were instructed to fixate on a white cross located at the center of the screen. The stimuli were displayed during 200 ms to avoid saccades during stimulus presentation. A trial consisted of two intervals with an inter-stimulus time of 500 ms; both intervals contained the same configuration. The rotational position of the stimuli was random in the first interval. In the second interval, the configuration was rotated an angle that was chosen randomly among 0°, 90°, 180°, or 270°. The intervals could be alternatively "reference" (carrying the reference speed of 4°/s) or "test" (carrying one of the seven test speeds RefSpeed ($1 + \Delta S$ with $\Delta S = 0.05$, 0.1, 0.15, 0.2, 0.25, 0.3, or 0.4). Subjects had to indicate by pressing a button which interval, first or second, contained the faster speed. We used a forced choice paradigm with the method of constant stimuli to obtain the subjects' psychometric functions. The speed discrimination thresholds were calculated by fitting Weibull curves to these functions. We used the Wichmann and Hill (2001a, 2001b) method to obtain the thresholds for a performance of 82%. To obtain the psychometric functions, the experiment was organized in blocks. In each block, only one of the three configurations was tested, and each of the seven test speeds was presented 30 times per block. Because we ran three blocks per configuration, each data point comes from 600 and 30 trials (90 trials per test speed).

2.2. Subjects

Five subjects participated in this study, two of the authors, and three paid naïve subjects. All of them had normal vision. The sessions began with a training period where feedback was provided: 20 trials per configuration were given. In the experimental sessions feedback was not provided.

2.3. Results and discussion

Fig. 2a shows, for the three subjects, the speed discrimination threshold (expressed as a percentage of reference speed) as a function of the relative angular distance between patches. It is important to note that each angle corresponds to a configuration of Verghese and Stone's (1997) experiment (see the caption of Fig. 2). Error bars represent one standard deviation.

The plot shows that thresholds increase as the patches are brought closer.

As we expected from Verghese and Stone's (1997) results, our data show a similar quantitative and qualitative behavior. Subject SD, for example, needs a 24% speed increment (about 1°/s of abso-

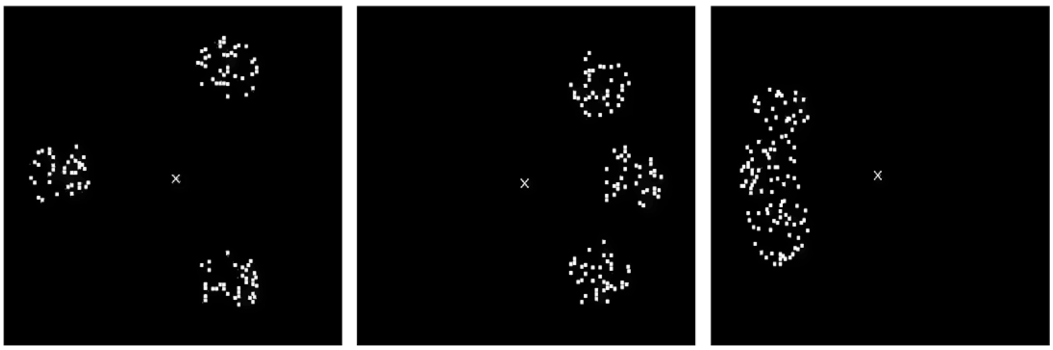

Fig. 1. Examples of the three spatial configurations used in Experiment 1. These configurations correspond, from left to right, to triangle (120°), three patches (40°), and banana (12.5°) of Verghese and Stone's (1997) study. It can be noted that rotational positions are different in the three examples. This position is chosen at random for the stimulus appearing in the first interval and is rotated 0°, 90°, 180°, or 270° in the second interval. Thanks to this procedure the subject cannot predict the position of the patches.

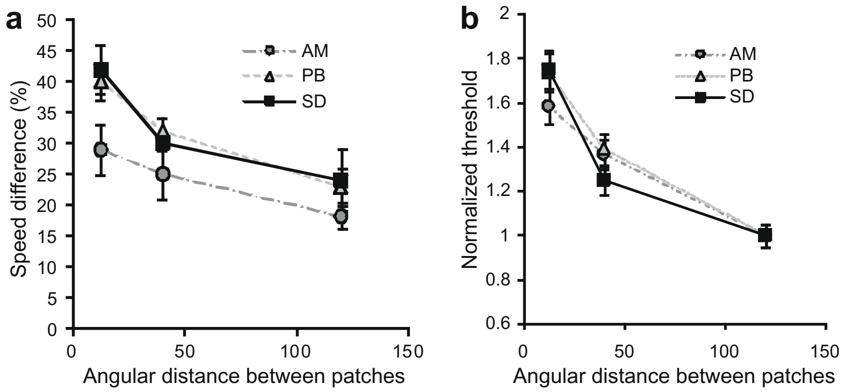

Fig. 2. (a) Speed discrimination threshold as a function of the relative angular distance between patches, for the three subjects. (b) Normalized speed difference as a function of the relative angular distance between patches. Although we parameterized the abscissa to compare the results of different experiments, each angular distance corresponds to a configuration of Verghese and Stone's (1997) experiments. 120° → triangle, 40° → three patches, and 12.5° → fused. The plot shows that the threshold decreases as the relative distance between patches is increased.

lute speed increment) to discriminate between test and reference for the 120° configuration (triangle), and needs a 42% speed increment (1.7°/s approximately) for 12.5° configuration (fused), i.e. near 70% more for absolute speed increment. Fig. 2b shows the data of Fig. 2a normalized respect to the threshold obtained for the 120° spatial condition. Because we expect an increment in the thresholds, we ran one-tailed *t*-tests with MINITAB software to estimate the significance of the variation of thresholds between conditions for each subject. Table 1 summarizes this analysis. It is important to clarify that these thresholds were obtained with eccentric vision, which explains the high values (24–45%) obtained in this situation respect to the typical thresholds (5–10%) obtained foveally.

These results show that the effect of the spatial configuration on speed discrimination, first showed by Verghese and Stone (1997) with sinusoidal gratings, holds for random dot patterns. Therefore, we can use this kind of stimuli with multiple patches of motion to explore whether this effect is forwarded to other tasks in which speed may be used as primary information, such is the case of motion segmentation.

3. Experiment 2: contour location vs. spatial arrangement

3.1. Methods

In this experiment, we studied whether the spatial configuration affects our ability to localize a contour defined by motion (segmentation task). To maintain equal dot densities in the two surfaces of the patch we used 60 dots per patch. The patches size and eccentricity were the same as in Experiment 1. The fused configuration was not used because dividing the single banana patch in two regions is not comparable to the other configurations in which three patches are divided. We then included a new configuration in which patches were separated by 80° (see Fig. 3). Stimuli were created in MATLAB with the Psychophysics Toolbox (Brainard, 1997) and Video Toolbox (Pelli, 1997), and displayed on a calibrated monitor (1024 × 768 pixels resolution, 60 Hz). As in the previous experiment, a subpixel motion procedure (Georgeson et al., 1996) was used to produce small speed differences in our stimuli. All dots moved horizontally at the same speed and direction (left or right), which was randomized on each trial. In case a dot reached the limit of the patch it was wrapped around. The contrast and the stimulus duration were the same as in Experiment 1. The fixation point was located at the center of the screen. The rotational position of the stimuli in this experiment was chosen randomly in each trial from the set: 0°, 90°, 180°, and 270°. The circular patches were divided in two regions by an imaginary line, which could be located 14 pixels (0.42° of visual angle) above or below the horizontal diameter. Each region contained different speeds; a fixed speed (S1) of 4°/s, and a speed that could get its value from a set of seven speeds ($S2 = S1 * (1 + \Delta S)$ with $\Delta S = 0.3$, 0.4, 0.6, 0.8, 0.95, 1.2 or 1.5). This was the independent variable of the experiment used to obtain the subjects' psychometric functions. These speeds could appear in the upper or lower region at random in each trial. The subject's task was to indicate whether the motion-defined contour was above or below the horizontal diameter (middle of the patch).

Table 1
Results of the statistical test of Experiment 1. Each row compares the thresholds between two conditions among subjects (columns).

	AM	PB	SD
120–40	$T(3) = -2.4$; $p < 0.05$	$T(3) = -4.32$; $p < 0.05$	$T(3) = -2.02$ $p = 0.09$
40–12.5	$T(3) = -1.49$; $p = 0.11$	$T(3) = -8.17$; $p < 0.05$	$T(3) = -4.98$; $p < 0.05$
120–12.5	$T(3) = -3.22$; $p < 0.05$	$T(3) = -6.93$; $p < 0.05$	$T(3) = -4.87$; $p < 0.05$

We used a forced choice paradigm with the method of constant stimuli to obtain the subjects' psychometric function. The thresholds were defined as the speed increment of the variable-speed-surface respect to the fixed-speed-surface necessary to obtain a performance of 82% in the contour localization task and were calculated by fitting Weibull curves to the psychometric functions (Wichmann & Hill, 2001a, 2001b). The procedure used to obtain the psychometric functions was identical to that used in the first experiment.

3.2. Results and discussion

Fig. 4 shows, for the three subjects, the normalized threshold in the contour localization task as a function of the relative angular distance between patches.

The figure shows that increasing the relative distance between patches enhances the sensitivity in the contour localization task. For example, subject PB needs about 20% more of speed increment to localize the contour for 80° than for 120°, and about 40% more for 40° than for 80°. Table 2 shows that the effect of the relative distance between patches is significant, except between 120° and 80°.

Because there is an inversely proportional relationship between threshold and speed differences in motion-defined contour locali-

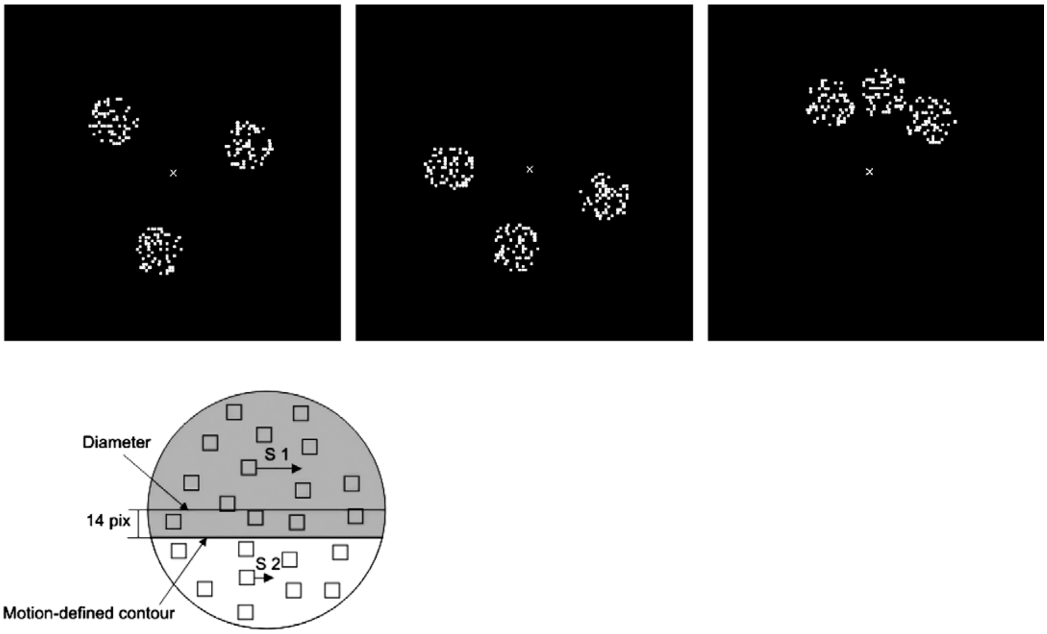

Fig. 3. On top, the three spatial configurations used in this experiment. In the bottom, the scheme showing how the illusory contour dividing the two surfaces was created (colors added with illustrative purposes only).

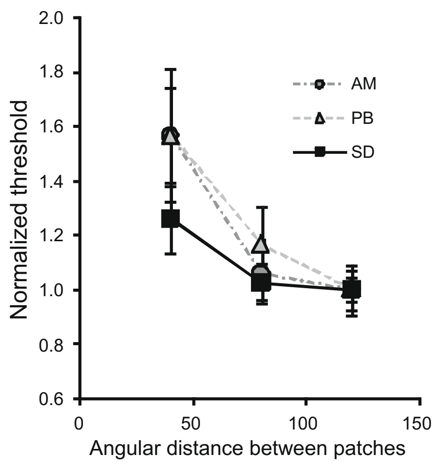

Fig. 4. Normalized thresholds as a function of the relative angular distance between patches for the three subjects. The threshold decreases with increasing relative angular distance between patches. Error bars represent one standard deviation from media.

Table 2
Results of the statistical test of Experiment 2. Each row compares the thresholds between two conditions among subjects (columns).

	AM	PB	SD
120–80	$T(3) = -0.87$; $p = 0.22$	$T(3) = -1.96$; $p = 0.094$	$T(3) = -0.3$; $p = 0.391$
80–40	$T(3) = -3.54$; $p < 0.05$	$T(3) = -3.11$; $p < 0.05$	$T(3) = -2.99$; $p < 0.05$
120–40	$T(3) = -4.12$; $p < 0.05$	$T(3) = -5.46$; $p < 0.05$	$T(3) = -3.0$; $p < 0.05$

zation tasks (Durant & Zanker, 2008; Rivest & Cavanagh, 1996) and because the stimuli have only speed cues, it is reasonable to think that changes in thresholds are related to the effect of the spatial layout on the estimation of speed. This supports our hypothesis that the increase in the precision of speed estimation produced by parsing the image into entities affects the subjects' performance in the segmentation task. Interestingly, the threshold increases more rapidly for segmentation than for speed discrimination, which in terms of absolute values, suggests that the effect of the spatial configuration is stronger for segmentation. This extra effect may be produced by some spatial interaction between different speeds belonging to different patches, which would appear only when the patches get close enough.

In the next experiment we propose to explore whether this effect also appears in other kinds of motion segmentation tasks such as speed-based transparency. Our hypothesis is that the speed differences necessary to perceive transparency will be affected by the spatial configuration since the visual system would represent transparency as when the different speeds are in adjoining regions (Braddick & Qian, 2001).

4. Experiment 3: transparency vs. spatial arrangement

4.1. Methods

We used the method of (Mestre, Masson, & Stone, 2001) to perform the experiment. In this method, two stimuli (transparent and dummy) are presented to the subject in two intervals. The transparent stimulus consisted of a random dot pattern containing two speeds: S1 and S2. The dummy, on the other hand, contained five speeds, which were calculated in such a way that both, transparent and dummy stimuli had the same mean speed so that subjects were not able to perform the task based on global speed cues (MS (mean speed) = 4°/s; S1 (max speed) = MS $*$ $(1 + \Delta S/2)$; S2 (minimum speed) = MS $*$ $(1 - \Delta S/2)$; S3 = (S1 − MS)/2; and S4 = (MS − S2)/2. With ΔS = 0.3, 0.4, 0.6, 0.8, 0.95, 1 or 1.25, which correspond to the range of constant stimuli). The patches were divided into horizontal bands of 0.12° width, each one of which contained one speed (see scheme of Fig. 5). The assignment of the speeds to the bands was quasi-randomized with the restriction that, in the dummy, the slowest and the fastest speeds could never be located in adjacent bands to avoid judgments based on this large speed difference. The direction of motion of transparent and dummy stimuli could be randomly right or left in each trial. The size of dots and patches and the stimu-

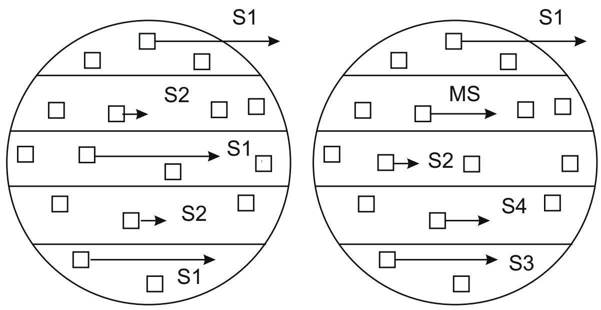

Fig. 5. The scheme shows how test (transparency) and dummy were created in Experiment 3. The transparent stimulus (left) contains only two speeds, v1 and v2. The dummy (right) contains five different speeds ranging between v1 and v2. These two speeds cannot appear in adjacent bands.

lus duration as well as the manipulation of the patches angular position were identical to those used in the first experiment. The order of presentation of transparent and dummy stimuli was random, and subjects had to indicate which interval contained the transparent stimulus. The independent variable of the experiment was the difference between v1 and v2, which was calculated as the product of the mean speed by an increment factor. We used a 2AFC paradigm with the method of constant stimuli to obtain the subjects' psychometric functions. The speed increment thresholds were calculated by fitting Weibull curves to these functions. We used the Wichmann and Hill (2001a, 2001b) method to obtain the thresholds for a performance of 82%. To obtain the psychometric functions, the experiment was organized in blocks. In each block, only one of the three configurations was tested, and each of the seven speed differences was presented thirty times per block. Because we ran three blocks per configuration, each data point comes from 600 and 30 trials (90 trials per test speed difference).

4.2. Results and discussion

Fig. 6 shows the normalized thresholds as a function of the stimulus configuration for the three subjects. Results show a similar tendency to that observed in the previous experiment: increasing the angular separation between patches reduces the threshold associated with speed discrimination. However, the effect of the spatial configuration in this case appears clearly weakened respect to that observed for segmentation of two adjoining surfaces (see Table 3).

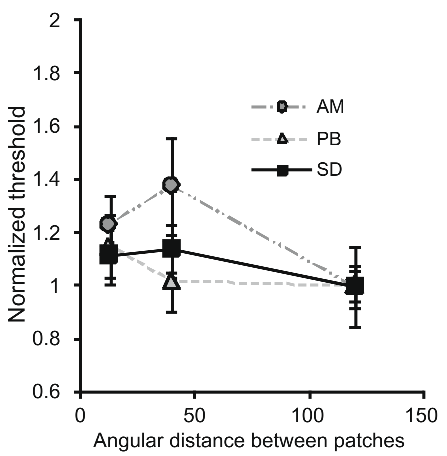

Fig. 6. Normalized speed increment thresholds as a function of the relative angular distance between patches for the subjects. Data show a systematic but little decrease of the threshold with increasing angular distance in the three subjects.

Moreover, two of the three subjects show a different tendency between 12.5° (fused) and 40°. One of these subjects presents no change from 12.5° to 40° and the other presents an increase of the threshold in this interval, which does not follow the tendency found for speed discrimination in the first experiment. These results would challenge the use of a unique explanation for both segmentation experiments. We wonder whether the attenuated effect obtained for transparency can be explained by the greater difficulty of the task or rather, there are differences in the mechanisms processing these two types of segmentation. In the following experiment, we modified the stimuli to reduce the difficulty of the task by increasing the bands' size of the transparent stimulus and by randomizing the positions of the dots in the dummy, and tested whether this modifications increase the effect of the spatial configuration on motion transparency. Moreover, we included in this experiment the angular separation of 80° to allow a more complete comparison with Experiment 2. The size of the bands was 0.2° and 0.5°, such that subjects still perceived the stimuli as transparent. All subjects reported that the task became easier as the size of the bands increased, which was reflected in the absolute thresholds (around 100% for 0.12°, and 70% for 0.5°). Fig. 7a and b show the results for 0.2° and 0.5°, respectively. In both situations, the curves do not present a consistent tendency across subjects.

Consequently, the average thresholds (dark solid lines) suggest a little or null effect of the spatial configuration on the perception of transparency for both bands' size. These results would strengthen the need of finding an alternative explanation for the differences found in the two types of segmentation used in this study.

5. General discussion

In the first experiment, we showed that parsing a moving random dot stimulus affects its speed perception in the same manner as it was shown by Verghese and Stone (1997) for sinusoidal gratings. These authors proposed that the decrease of the speed discrimination threshold that appears when the stimulus consisted of multiple patches of motion is because the speed estimation is based on the combination of multiple independent samples, which gives a more precise estimate with respect to that obtained from a single measurement. This is consistent with the model of Bravo and Watamaniuk (1995) who proposed that motion computation consists of, at least, two stages. A first stage that extracts coarse local motion signals, which are used to segment the image, and a second stage that uses those local signals to obtain a more precise estimation of speed through a spatio-temporal integration process. However, if we apply this idea to our second experiment, the model would need an extra stage to explain that the thresholds for the localization of a speed-difference-defined contour improve with increasing angular distance between patches. In fact, the use of this framework to explain our data requires the inclusion of an interaction between these stages such that an improvement in the estimation of speed results in a better segmentation. This third recursive stage agrees with the theoretical point of view of Yuille and Grzywacz (1998). They proposed three successive stages (mea-

Table 3
Results of the statistical test of Experiment 3. Each row compares the thresholds between two conditions among subjects (columns).

	AM	PB	SD
120–40	$T(3) = -3.27$; $p < 0.05$	$T(3) = -0.16$; $p = 0.44$	$T(3) = -2.42$; $p < 0.05$
40–12.5	$T(3) = 1.19$; $p = 0.84$	$T(3) = -1.45$; $p = 0.12$	$T(3) = 0.3$; $p = 0.61$
120–12.5	$T(3) = -2.84$; $p < 0.05$	$T(3) = -1.37$; $p = 0.13$	$T(3) = -1.68$; $p = 0.096$

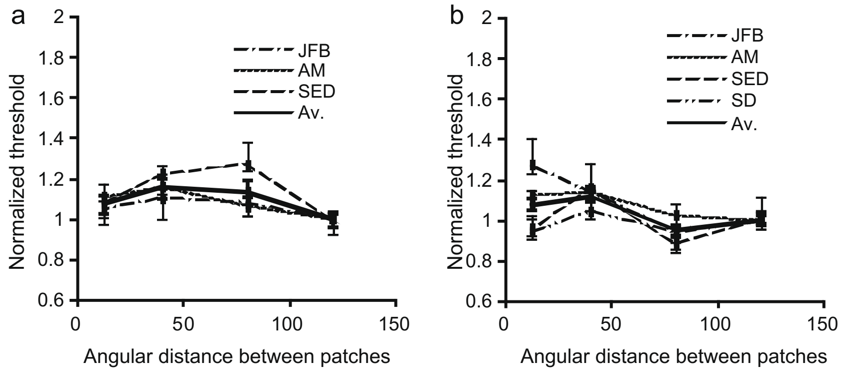

Fig. 7. (a) Normalized speed increment thresholds as a function of the relative angular distance for a band size of 0.2°. (b) The same as in (a) but for a band size of 0.5°. See the text for details.

surement, segmentation and modeling) interacting one with each other to solve the problems that could appear in the computation of the different motion parameters. According to this framework, the brain would try to group those areas with similar motion statistics by fitting different motion models, which would produce a better estimate of such motions by constraining the local measurements. It could be proposed that such integration occurs in MT and/or MST cells (Duffy & Wurtz, 1991a, 1991b; Graziano, Andersen, & Snowden, 1994; Lagae, Maes, Raiguel, Xiao, & Orban, 1994; Maunsell & Van Essen, 1983; Tanaka, Fukada, & Saito, 1989; Tanaka & Saito, 1989; Priebe, Cassanello, & Lisberger, 2003), and that those signals would be re-inserted in previous stages such as V1 or MT cells (Hupé et al., 2001; Perrone & Thiele, 2002; Priebe, Lisberger, & Movshon, 2006), where the coarse local motion signals would be produced. Inside this framework and with the hypothesis that transparency could be mentally represented as when the different speeds are in adjoining regions (Braddick et al.) it would be expected similar results for the case of transparency, in which the segmentation occurs between superimposed layers. However, data showed in Figs. 6 and 7 reveal that the spatial configuration does not affect the thresholds for transparency along a range of bands' size. How can we explain this discrepancy?

The first two experiments support the idea that there is a spatial pooling of local motion signals that produces a better estimation of speed (Fig. 2), which would be later reflected in the segmentation of adjoining surfaces (Fig. 4). On the other hand, the third experiment would suggest that such a pooling does not appear or is weak in the case of transparency, which is consistent with the work of Watson and Eckert (1994) who found no evidence for spatial pooling beyond the level of local motion detectors by using striped stimuli, similar to those used in the third experiment of the present study. Importantly, the authors emphasize that their findings do not mean that "such pooling does not occur but only it does not occur in the pathway used in this task." This rationale supports the idea that we would be facing two different mechanisms: one including both a spatial integration of local signals, and a feedback among stages; and other mechanism performing the segmentation by using only local information. Consistently, Mestre et al. (2001) and Masson et al. (1999) showed that the segmentation of two transparent layers is constrained by a process operating at a small spatial scale, which suggests that MT, which would be in charge of the integration process, would not be a good candidate to resolve transparency but that V1 would play the central role in this task.

These two mechanisms could be thought as a process that makes use of the most reliable information available in the system to perform a task. In the case of two adjoining surfaces with different speeds, an integration process may improve the speed estimation of each surface by keeping the information of the two different speeds but, in the case of transparency, an integration in the scale of MT would blend the local signals and thus, losing the information given by the speed difference. Therefore, to perceive the transparency, we need to get the information before the integration. This is consistent with the studies showing that the visual system is capable of picking up the local motion information while perceiving the global motion (Atchley & Andersen, 1995; Navon, 1981; Watamaniuk & Sekuler, 1992).

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