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Visibility versus accountability in pooling local motion signals into global motion direction

Aire Raidvee · Kristiina Averin · Jüri Allik

Abstract The human observer is surprisingly inaccurate in discriminating proportions between two spatially overlapping sets of randomly distributed elements moving in opposite directions. It was shown that observers took into account an equivalent of 74 % of all moving elements when the task was to estimate their relative number, but only an equivalent of 21 % of the same elements when the task was to discriminate between opposite directions. It was concluded that, in the motion direction discrimination task, a large proportion of the signal from all of the elements was inaccessible to the observers, whereas the majority of the signal was accessible in a numerosity task. This type of perceptual limitation belongs to the attentional blindness category, where a strong sensory signal cannot be noticed when processing is diverted by parallel events. In addition, we found no evidence for the common-fate principle, as the ability to discriminate numerical proportions remained the same, irrespective of whether all estimated elements were moving coherently in one direction or unpredictably in opposite directions.

Keywords Motion perception · Pooling motion information · Numerosity discrimination · Visibility and accountability

A. Raidvee (✉) · K. Averin · J. Allik
Department of Psychology and Estonian Center of Behavioral and Health Sciences, University of Tartu,
Tiigi 78,
Tartu 50410, Estonia
e-mail: aire.raidvee@ut.ee

J. Allik
Estonian Academy of Sciences,
Kohtu 6,
Tallinn 10130, Estonia

The human observer is surprisingly inaccurate in discriminating proportions between two spatially overlapping sets of randomly distributed elements moving in opposite directions (Raidvee, Averin, Kreegipuu, & Allik, 2011). For a wide range of stimulus sizes, decisions about motion direction are made as if only a very limited number of elements (in some cases, less than 0.5 %) were taken into account, even if the motion direction of each element in isolation can be determined with almost absolute certainty. This is very intriguing, since observers seem to be under no illusion about the actual number of moving elements. They are well aware of the large number of moving elements on the screen, but they seem to lack introspective knowledge about how many of these motion elements contribute to answers about the dominant motion direction. Thus, from the total signal carried by a large number of visible moving elements, only a fraction is taken into account in determining global motion. Is the remainder of the global signal invisible to the observer?

The main challenge we faced in this study was the distinction between *visible* and *accountable* information. Memory researchers, for instance, realized long ago that not all potentially available memory content is necessarily accessible at every instance of recall from the memory (Tulving & Pearlstone, 1966). Except perhaps in the case of ideal observer analysis (cf. Rose, 1948), it is relatively rare that perceptual analysis makes the distinction between potentially available and actually used information (Allik & Pulver, 1994; Burgess & Barlow, 1983). However, in several well-described experimental protocols (the attentional blink, crowding, dual task, etc.), a strong sensory signal cannot be noticed when attention is distracted by other stimuli (Dehaene & Changeux, 2011; Kanai, Walsh, & Tseng, 2010; Sergent, Baillet, & Dehaene, 2005). These situations are typically called *attentional blindness*, as opposed to *perceptual blindness*, which is caused by

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the degradation of a weak sensory signal itself (Kanai et al., 2010).

In this article, we propose a different approach to quantifying the distinction between the visibility and accountability of motion elements. As in our previous study (Raidvee et al., 2011), we varied the proportions of leftward- versus rightward-moving elements to construct the psychometric function for the discrimination between opposite motion directions. On the basis of this psychometric function, it was possible to determine the number of moving elements that were taken into account in making decisions about global motion direction. The observer's decisions could be described by the Bernoulli trial scheme, in which the observer randomly selects out K elements from the actual number of motion elements, N, that are present in the stimulus, of which N_R are moving rightward and N_L leftward. The rational decision rule is very simple: If the number of the rightward-moving elements K_R in the selection exceeds the number of the leftward-moving elements K_L (i.e., $K_R > K_L$), then the rightward direction is chosen; otherwise, the leftward direction is chosen. If the numbers of accounted elements moving in opposite directions happen to be equal ($K_R = K_L$), then the choice between the two response categories is random, with equal probabilities of either (assuming that there is no response bias). Thus, the ratio of the accounted-for motion elements, K, to the actually presented number of motion elements, N, (together with the actual value of N) determines the slope of the psychometric function. Given a certain N, it is possible to determine from the slope of the psychometric discrimination function the number of motion elements K that were taken into account in making decisions about the dominant motion direction. The formal expression of the response model just described is given in the Appendix.

As already noted, unlike the ideal observer in determining motion direction, a human observer is limited to only a small fraction of the moving elements, $K \subset N$, which is used for inferring the global impression of movement. Thus, many motion elements are visible yet ignored by the observer when the decision about the global motion direction is made. How can the total number of moving elements that are visible but not necessarily used for the determination of the motion direction be ascertained? One potential method is numerosity discrimination. Exactly the same motion element stimuli can be presented and the observer asked about their relative number. When the observer is instructed to discriminate the relative numbers in the two sets of moving elements, the decision obviously needs to be made on the basis of the quantification of as many elements as possible from these two sets. On the basis of the slope of the discriminating function, it is possible (given a certain value of N), again, to estimate how many elements from both sets were actually taken into account. This number is presumably larger than the number on the basis of which decisions about the motion direction are made. We believe that the differences in the outcomes for these two tasks—motion and numerosity discrimination—could be used as a first approximation to what could be called the *visibility* and *accountability* of motion elements: From a large number of motion elements that are visible when numerosity decisions are made, a supposedly smaller fraction are taken into account for the determination of the global-motion impression.

It is well known that a common motion vector is a strong grouping factor of visual elements. Kurt Koffka (1935/1963) probably coined the term *common fate*, which played an important role in the formulation and spread of the Gestalt principles. However, like many other Gestalt "laws," the common-fate principle is difficult to formalize and has usually been communicated through visual examples alone (for some exceptions, see Edwards, 2009; Sturzel & Spillmann, 2004; Uttal, Spillmann, Sturzel, & Sekuler, 2000). In this study, for the quantification of the difference between visibility and accountability, we presented two spatially separated sets of moving elements by asking the observer to determine, as a first task, which of these two sets contained more elements; as a second task, we asked the observer in which direction (right versus left) either quantitatively identical replica of the stimulus appeared to move; and as a third task, we asked in which direction the two quantitatively identical replicas of the stimulus appeared to move.

For the first task—numerosity discrimination—it was irrelevant in which direction the elements of these two sets were moving, or whether they were moving at all. However, it is possible that the coherence among motion elements, as Gestalt psychologists claim, increases their conspicuity. If this holds true, then the numerosity discrimination between two sets of elements moving coherently in one direction would be expected to be more accurate than the discrimination between two sets of elements that move incoherently in opposite directions. This difference, provided that it exists, would be a novel way to operationalize the common-fate principle. It would thus be possible to say precisely how many more elements have been taken into account in a coherently moving pattern than in an incoherently moving set of elements of the same size.

One surprising corollary of the limited capacity for motion discrimination is the almost complete irrelevance of the total number of motion elements. If an observer's decisions are based on a limited subset of elements, then the duplication of a motion pattern that contains elements moving in opposite directions in an adjacent area of the visual field would not be expected to improve motion direction discrimination performance. In many other areas of visual perception, however, it is known that the duplication of the test stimulus leads to enhanced detection or recognition performance (e.g., Meese & Williams, 2000). Our intuition is also that doubling the stimulus would increase the probability of noticing its critical attributes. However, this may not be the case with discriminating between opposite motion directions, which is based on an account of a relatively small and fixed number of motion elements. Nevertheless, it would be intriguing to test this prediction, which may, to many, seem counterintuitive.

Method

Subjects

We ran four female subjects, referred to as S1, S2, S3, and S4, with normal or corrected-to-normal visual acuity and with no reported history of visual disorders. Their ages ranged from 20 to 32; three of them had prior experience with psychophysical experiments, but two were naïve to the concept of the present experiments.

Apparatus

Stimuli were generated using a Cambridge Research Systems *ViSaGe* image generator driven by a Pentium computer. The stimuli were displayed, at a viewing distance of 170 cm, on a Mitsubishi Diamond Pro 2070SB 2200 monitor (active display area 20 in.), operating at a refresh rate 140 Hz, with a spatial resolution of 1,024×769 pixels. A schematic view of the stimulus configurations is shown in Fig. 1. The physical properties of the stimulus displays were similar for all three types of experiments. The stimuli consisted of a set of identical circles, each with a circumference of 3 arcmin and a luminance of 67 cd/m^2, which were simultaneously presented onto either one or two background areas: that is, two adjacent elliptical dark areas with luminance close to zero and lengths of the horizontal and vertical axes of 5.05º and 4.7º, respectively. The elliptical backgrounds were surrounded by a rectangular area of luminance 7.5 cd/m^2, filling the rest of the screen, thus subtending 13º horizontally and 9.8º vertically. The distance between the elliptical areas was equal to their distance from the display boundaries, 0.97º. Each element was surrounded by an inhibitory area that prohibited the elements from being closer than 7.6 arcmin to each other. The minimal distance of an element from the edge of the test area (i.e., the elliptical background) was 15.2 arcmin. The observers were instructed to fixate on the center of the screen.

Motion discrimination

In each trial, two frame stimuli of N elements were presented on the screen. The individual frames were separated by an interstimulus interval of 30 ms and lasted for 100 ms.

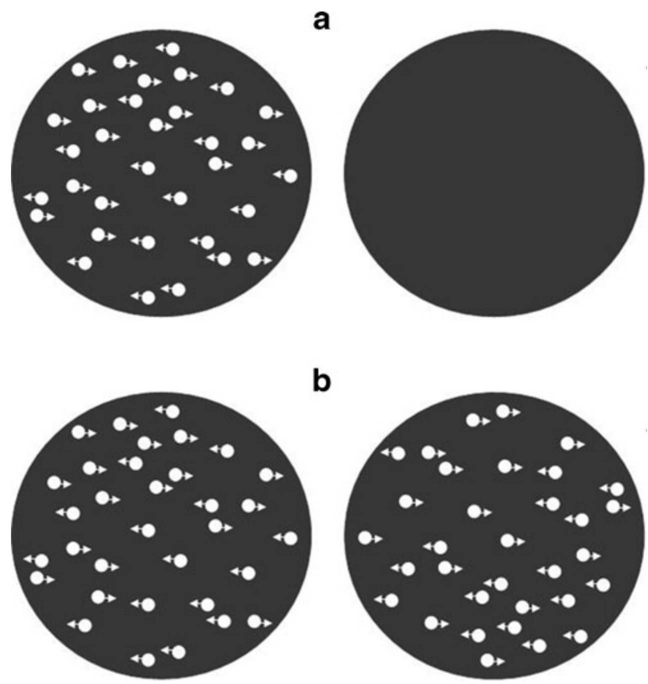

Fig. 1 Stimulus configurations in the three types of experiments: Schematic views of the stimulus configurations used in (**a**) the motion discrimination task with the single test area, and (**b**) both the motion discrimination task with the double test area and the numerosity discrimination experiment

Each element in the second frame was displaced 11.4 arcmin to the left or the right of its original position in the first frame. The proportions of leftward-displacing (N_L) and rightward-displacing (N_R) elements were varied, with the observers' task being to indicate in which direction, to the left or the right, they saw a larger number of elements moving. If all elements were moving in the same direction, then observers had no problems identifying motion direction, since coherently shifting elements produced a very compelling impression of motion.

In the first series of experiments ("single test area"), motion elements appeared in only one of the two test areas (see Fig. 1A). There was no previous information on which of the two areas contained motion elements or which test area would remain empty. Motion elements were assigned to either the left or right area randomly, with equal probability. The total number of elements in a test area was constant at 33, with the relative proportions of rightward-moving elements, N_R, versus leftward-moving elements, N_L, randomized throughout the experimental session and varying at six levels: 10:23, 13:20, 16:17, 17:16, 20:13, and 23:10. Each condition (corresponding to one ratio) was administered 200 times (40 times in five separate sets): 100 times with the elements appearing in the left test area, and 100 times with the elements appearing in the right area.

In the second series of experiments ("double test area"), both of the test areas were filled with moving elements (Fig. 1B). Each test area contained N_L elements displacing to the left and N_R elements displacing to the right. The spatial configurations of the elements in the two test areas were not identical and were determined randomly for each test area. As in the single-test-area experiment, the observers' task was to indicate in which direction they saw the larger number of elements moving. Thus, relative to the single-test-area task, in this series of experiments, the total number of motion elements (N) and the numbers of rightward-displacing (N_R) and leftward-displacing (N_L) elements were doubled. The total number of elements equaled 33 for each test area (thus totaling 66), with the relative proportions of N_R versus N_L randomized over the experimental session and varying at eight levels that were equal for both areas, and thus totaled 14:52, 20:46, 26:40, 32:34, 34:32, 40:26, 46:20, or 52:14 across the two areas. Each condition (corresponding to one proportion) was administered 100 times (20 times in five sets).

Numerosity discrimination

In the numerosity discrimination task, both test areas contained identical motion elements, some of which were moving to the left and others to the right. Unlike the motion discrimination task with double test areas, the numbers of motion elements in the left and the right test areas were not equal and varied from trial to trial.

The observer's task was to ignore motion information and to indicate which of the two test areas, the left or the right, contained more elements. There were two types of trials, corresponding to coherent- and incoherent-motion conditions. In the coherent-motion ("common-fate") trials, all N elements in both test areas were moving in only one direction, to the left or to the right. In the incoherent-motion trials, half of all elements were moving to the left and the remaining half to the right. The total number of moving elements remained constant at N = 66, but the exact proportions assigned either to the left or to the right test area were randomized across individual trials and varied at six levels: 26:40, 29:37, 32:34, 34:32, 37:29, and 40:26. Each proportion was repeated 300 times (30 times in ten sets): 100 times for the common-fate condition, with all elements moving rightward; 100 times with all elements moving leftward; and 100 times with half of the elements moving leftward and the other half moving rightward. All conditions were randomized within one experimental session.

The time provided for responding was always 3 s. If the subject did not respond, the trial was cancelled and repeated later in a random position among the remaining trials. All stimulus conditions were randomized within one experimental session.

Data analysis

In order to find out the number of elements, K, that the subjects based their decisions on in each type of experiment, the hypergeometric response model (formalized in the Appx.) was fitted to the data. In order to account for the bias inherent in the responses, the empirical psychometric curves were shifted along the abscissa so that the mean response would be equal to .5. As this kind of transformation would further prohibit the direct application of discrete computational methods in the assessment of model fit, we chose to compare the empirical and theoretical curves via the cumulative normal distribution. Specifically, for each empirical function, the best-fitting theoretical model (out of all possible theoretical models) was the one with the smallest calculated area integral between the functions (i.e., the two normal approximations of both the empirical and theoretical response curves). Finally, as an estimate of variance unexplained by the theoretical model, we found the ratio of the calculated area integral to 0.5 (the theoretical maximal area that can be observed between empirical and theoretical functions).

Results

The results are given in Table 1 and Figs. 2 and 3. We can estimate the discrepancy between the elements' visibility and accountability by comparing the experimental series in which exactly N = 66 elements were presented across the test areas as a two-alternative forced choice task. Decisions about the proportions of the leftward versus the rightward elements were made as if 17, 9, 19, and 11 elements had been taken into account by observers S1, S2, S3, and S4, respectively. In the relative-numerosity discrimination task, however, decisions were made on the basis of a considerably larger number of elements. There, the numerical proportion was decided as if 47, 51, 51, and 47 elements had been counted by observers S1, S2, S3, and S4, respectively. In terms of percentages, on average, 21 % (in the motion discrimination task) versus 74 % (in the numerosity discrimination task) of all elements were available for inspection. Roughly speaking, in the numerosity discrimination task, decisions were based on the taking into account of over three times more elements than in the motion direction discrimination task. Thus, we can conclude that, in the motion discrimination task, observers can see a considerable number of motion elements,

Table 1 Numbers of elements sampled by the best-fitting theoretical models in the different types of experiments

	S1	S2	S3	S4
Numerosity discrimination (N = 66)				
K	47	51	51	47
K/N (%)	71.21	77.27	77.27	71.21
S	0.0010	0.0004	0.0010	0.0004
%Error	0.207	0.084	0.206	0.088
%EV	99.79	99.92	99.79	99.91
Motion discrimination: Double test area (N = 66)				
K	17	9	19	11
K/N (%)	25.76	13.64	28.79	16.67
S	0.0014	0.0036	0.0015	0.0017
%Error	0.276	0.728	0.293	0.335
%EV	99.72	99.27	99.71	99.67
Motion discrimination: Single test area (N = 33)				
K	13	13	11	15
K/N (%)	39.39	39.39	33.33	45.45
S	0.0046	0.0004	0.0036	0.0037
%Error	0.930	0.087	0.716	0.748
%EV	99.07	99.91	99.28	99.25

N, number of elements on the display; K, number of elements sampled by the best-fitting hypergeometric model; S, area integral between the empirical versus best-fitting theoretical curves; %Error, $S/0.5 \cdot 100$, the percentage of variance unexplained by the theoretical model; %EV, the percentage of variance explained, $(1 - S/0.5) \cdot 100$ %.

many of which they are not able to determine the actual motion direction for.

One could argue that this inability to perceive or determine the actual motion direction was due to the mutual cancellation of opposite motion vectors between adjacent elements. Previous work has indicated that the low efficacy of motion direction discrimination in this type of display is not improved in the case of orthogonally directed motion vectors (Raidvee et al., 2011). As numerosity discrimination is not perfect, either, it is conceivable that the mutual cancellation of elements would somehow interfere with this process, as well. In order to test for this possibility, direction discrimination was compared among the two common-fate conditions and one bidirectional condition. These results are depicted in Fig. 3, and they clearly indicate absolutely no effect for the common-fate principle on the observers' capacity for numerosity discrimination. The slope of the psychometric function remained virtually unaltered, whether all elements moved coherently in one direction or moved unpredictably in opposite directions.

As expected, motion discrimination performance was not improved substantially by replicating the stimulus in an adjacent area. Thus, when the motion elements were presented in only one test area with N = 33, the decisions about the proportions of the leftward versus rightward elements in the single-test-area condition were based as if 13, 13, 11, and 15 elements had been taken into account by observers S1, S2, S3, and S4, respectively (see Fig. 2, second vs. third row). In terms of variance in responses (σ), the discrimination of motion direction in the single-test-area condition was roughly on par with that in the double-test-area condition. Nevertheless, in terms of the number of elements sampled, in two subjects the discrimination was facilitated, whereas in the other two it was hindered, by the stimulus replica. Nevertheless, the mean numbers of elements taken into account in the two tasks differed by only one: 13 in the one-test-area and 14 in the double-test-area experiment. As the differences in the estimated numbers of elements sampled by the subjects were neither large nor systematic (+4 and +8 for subjects S1 and S3, as compared to –4 and –4 for subjects S2 and S4, respectively), it is hard to arrive at any conclusion about the effect of stimulus duplication on motion discrimination decisions, other than to say that the effect is probably not extensive. Together with our previous findings, we can conclude that the slope of the psychometric function is, on the whole, insensitive to the total number of moving elements, provided that it is expressed as a function of the proportions of leftward- and rightward-moving elements.

Discussion

The results present three major points of interest. First, confirming our previous findings (Raidvee et al., 2011), we found our observers to be very poor at discriminating direction between two spatially overlapping sets of randomly distributed elements moving in opposite directions. Even in displays containing a relatively small number of elements (N = 66), observers' decisions were based on only about one-fifth of these elements. In our previous study, the data indicated that, typically, motion direction information of only 4 ± 2 elements was taken into account when global motion direction was inferred from local motion signals pointing in opposite directions. However, in the present study we saw that, by increasing the contrast of the motion elements by three times, it was possible to somewhat increase the size of the sample on the basis of which global motion direction was inferred. Nevertheless, even in these improved conditions, the motion direction was ignored for the vast majority of elements. It is likely that we reached the natural limit: Exceeding this number would be very difficult, if not impossible.

It seems that observers are blind to the motion information carried by the majority of motion elements. The comparison with the numerosity discrimination task

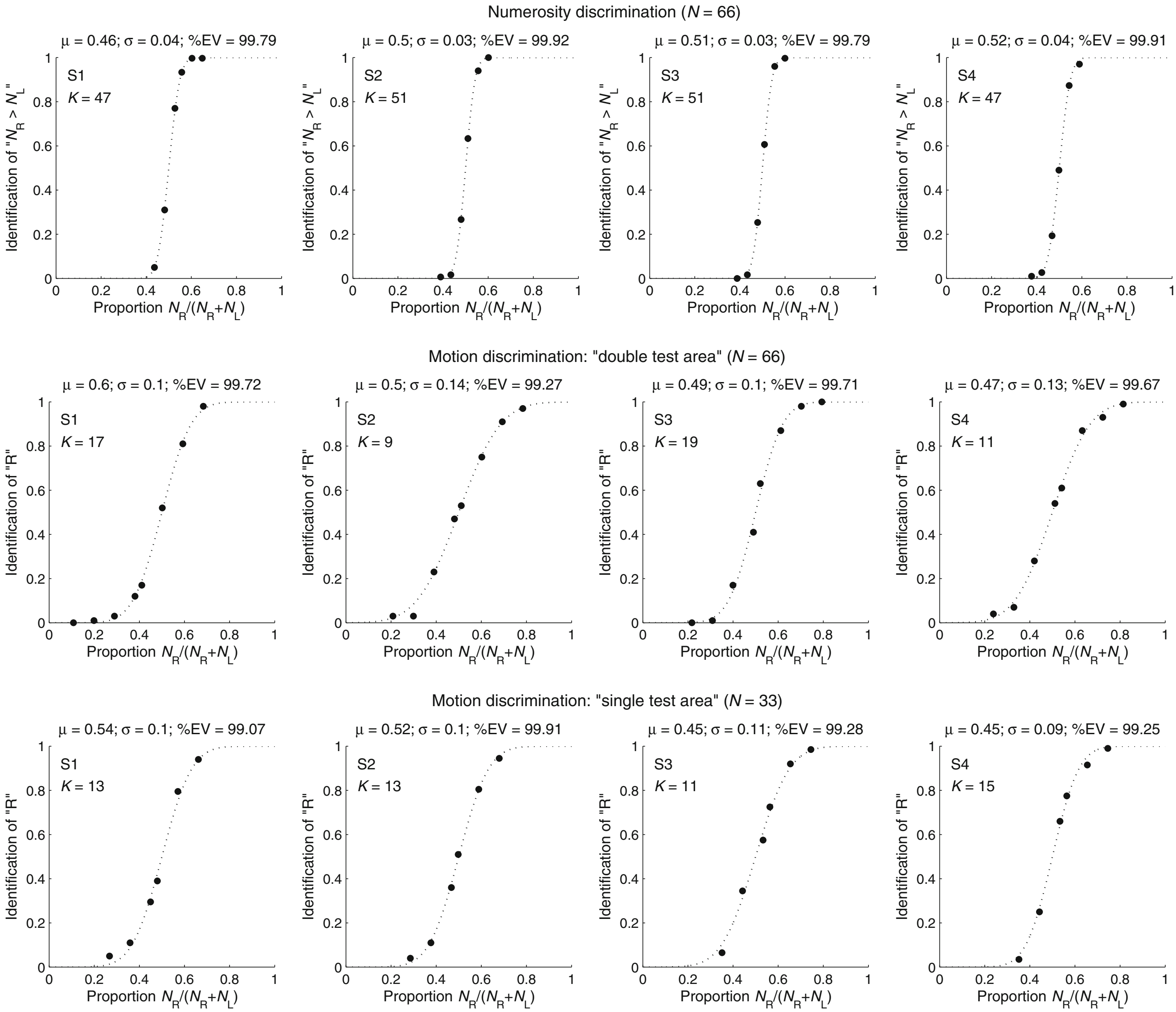

Fig. 2 The best-fitting normal approximations to theoretical hypergeometric models (dotted line) versus the empirical data points. These give the choice probabilities as a function of the proportions of the chosen response category for the four observers and the three tasks: numerosity discrimination (top row), motion discrimination with a double test area (second row), and motion discrimination with a single test area (bottom row). μ, mean of the approximated psychometric function; σ, standard deviation (slope) of the psychometric function; %EV, the percentage of variance explained, $(1 - S/0.5) \cdot 100$ %, where S is the area integral between the empirical versus best-fitting theoretical curves; N, total number of elements in the display; N_L, total number of leftward-moving elements in the display; N_R, total number of rightward-moving elements in the display; K, estimated number of the motion elements taken into account in the decision process

shows that many of these neglected elements are seen and have been taken into account when the observer is asked to estimate which side, left or right, contains more elements, irrespective of their motion direction. Thus, about two-thirds of all elements are visible with respect to the numerosity task, but the qualities required for pooling local-motion information are not present. In our previous study (Raidvee et al., 2011), we demonstrated that the inaccessibility of motion information is not due to the cancellation or nulling of opposite motion vectors between closely located neighbors. The same extent of perceptual limitation was observed between orthogonally oriented motion vectors, which are known to be processed by separate visual mechanisms (Levinson & Sekuler, 1975).

What is the mechanism by which this perceptual limitation operates? Since the direction of each motion element can be determined with nearly absolute certainty if the element is presented in isolation, this means that the extraction of available motion information is distracted by other elements present on the screen. In this respect, the situation is very similar to other well-studied experimental conditions (the attentional blink, crowding, dual task, etc.) in which a

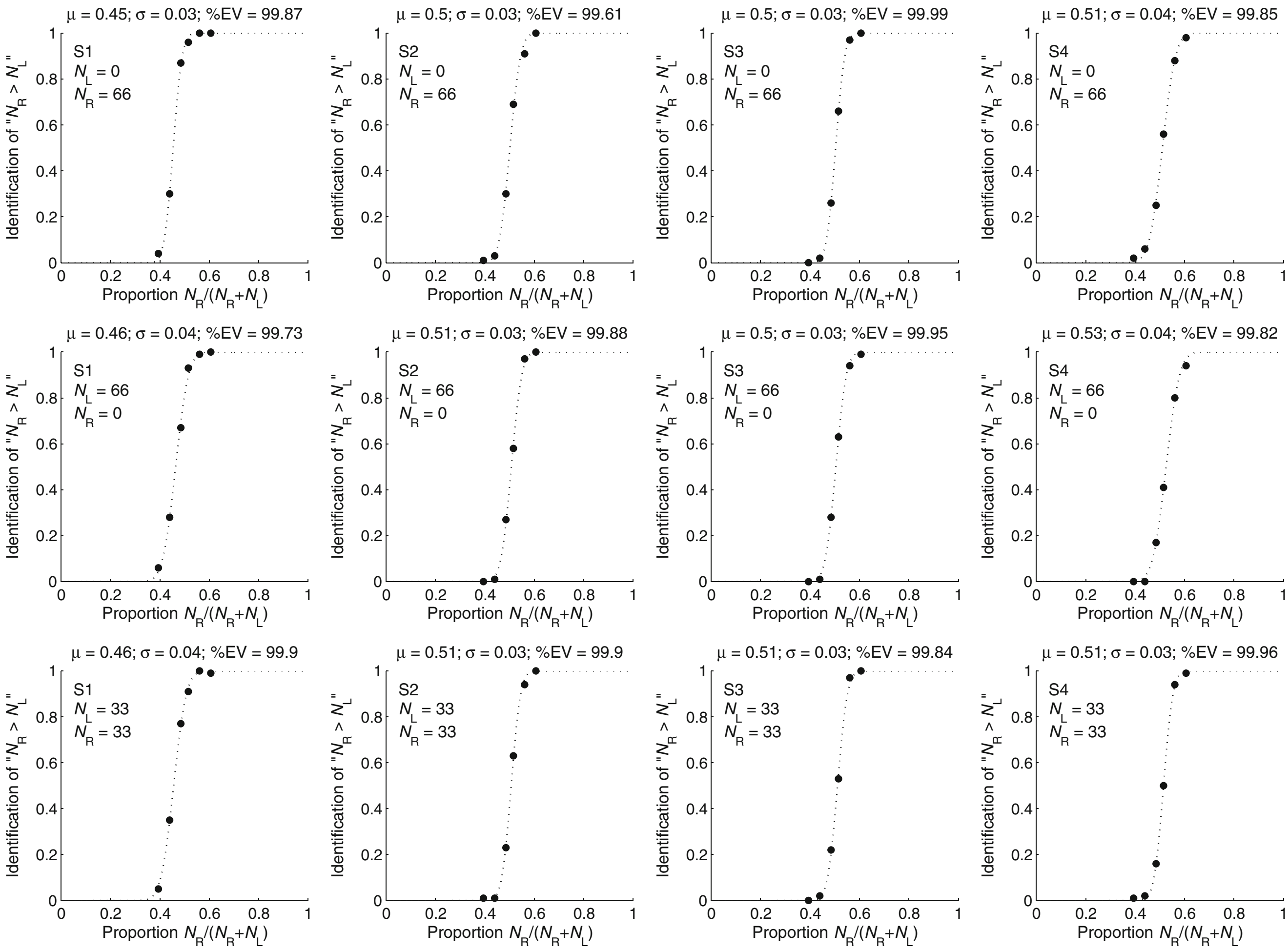

Fig. 3 Common-fate principle: The best-fitting normal approximations (dotted line) versus the empirical data points. These give the choice probabilities as a function of the proportions of the chosen response category for the four observers in the numerosity discrimination tasks with all elements moving rightward (top row), all elements moving leftward (second row), and 33 elements moving leftward and 33 moving rightward (bottom row). μ, mean of the approximated psychometric function; σ, standard deviation (slope) of the psychometric function; %EV, percentage of the explained variance, R^2; N_L, total number of leftward-moving elements in the display; N_R, total number of rightward-moving elements in the display

strong sensory signal cannot be noticed when processing is diverted by some other events (Andrews, Watson, Humphreys, & Braithwaite, 2011; Kanai et al., 2010). Unfortunately, we have very little information about the spatial, temporal, or other limits of this form of perceptual limitation.

Second, the replication of the stimulus in another inspection area was not beneficial for the decision about which direction more visual elements were moving in. If perception is indifferent to the total number of elements, then the psychometric curves represented as a function of the proportion of moving elements, $N_L/(N_L + N_R)$, should have equal slopes. As in our previous study (Raidvee et al., 2011), we were not able to observe any systematic change in the slopes of psychometric functions while the number of moving elements was duplicated in another inspection area. Consequently, even though with a larger array of motion elements, observers were able to determine the motion parameters of a large number of elements, this number was fairly small, relative to the total number of moving elements. Thus, it appears as if the human observer is temporarily motion blind toward the majority of elements moving unpredictably in opposite directions. Although we are not the first to report such wastefulness in the coding of motion (Braddick, Wishart, & Curran, 2002; Edwards & Greenwood, 2005; Suzuki & Watanabe, 2009), some questions remain to be answered about the ubiquitous textbook statement that our very survival critically depends on being able to perceive movement accurately (see, e.g., Palmer, 1999).

Finally, we found that the common fate of moving elements has negligible, if any, effect on the numerosity discrimination between two sets of moving elements. Irrespective of whether all elements were moving coherently in one direction or incoherently in opposite directions, the ability to discriminate numerical proportion remained the same. Although in some cases the common-fate principle can be demonstrated (Sekuler & Bennett, 2001; Stürzel & Spillmann, 2004; Uttal et al., 2000), our results clearly contribute to the line of evidence showing that this principle cannot be considered universal. The common fate of moving elements may be beneficial in some other tasks, but it seems to provide no advantage when it comes to the estimation of their relative numerosity.

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Appendix

Formal expression of the psychometric model

The probabilities of a certain response for odd and even K, according to the hypergeometric response model, are given by Eqs. A1 and A2:

$$P_{hyp\{K\ is\ odd\}} = \sum_{i=1+\lfloor \frac{K}{2} \rfloor}^{K} \frac{\binom{N_L}{i}\binom{N_R}{K-i}}{\binom{N}{K}}, \quad K = 2k-1 \tag{A1}$$

$$P_{hyp\{K\ is\ even\}} = \sum_{i=1+\frac{K}{2}}^{K} \frac{\binom{N_L}{i}\binom{N_R}{K-i}}{\binom{N}{K}} + 0.5\frac{\binom{N_L}{\frac{K}{2}}\binom{N_R}{\frac{K}{2}}}{\binom{N}{K}}, \quad K = 2k \tag{A2}$$

where k is any positive natural number; N_L is the number of elements in the stimulus that are moving leftward or are presented in the left-hand test area (depending on the task); N_R is the number of elements in the stimulus that are moving rightward or are presented in the right-hand test area (depending on the task); N is the total number of elements in the stimulus ($N = N_L + N_R$); and K is the number of elements taken into account in the decision process.

For practical purposes, it is enough to consider either odd or even values of K only, as the equality Eq. A1 = Eq. A2 holds, given equal values for k (Raidvee et al., 2011).

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