Limited attention facilitates coherent motion processing

Isamu Motoyoshi Department of Life Sciences, The University of Tokyo, Tokyo, Japan

Taichi Ishii Faculty of Informatics, Kogakuin University, Tokyo, Japan

Miyuki G. Kamachi Faculty of Informatics, Kogakuin University, Tokyo, Japan

It has been suggested that sensitivities for visual motion are typically impaired by poor attention. Here, we show that limited attention paradoxically improves performance on a global motion detection task. Psychophysical experiments revealed that deliberately attending to an irrelevant stimulus enhanced sensitivity for detecting coherent motion in random-dot kinematograms but did not affect contrast and velocity sensitivity for local luminance motion. Subsequent experiments further demonstrated that the dual task reduced sensitivity for detecting spatial modulations in local motion direction and induced illusory motion assimilation. Additional measurements confirmed that the secondary task had no effect when attentional load was extremely high or when motion stimuli were presented peripherally. These results may be explained by the idea that limited attention dynamically expands the spatial extent of motion integration by reducing center-surround interactions at high-level motion processing.

Introduction

Attention is commonly associated with enhanced information processing in the visual cortex. A number of studies have explored the neural and computational bases of attentional facilitation and especially so for motion processing (Maunsell & Treue, 2006; Raymond, 2000). Psychophysical evidence demonstrates that attention enhances the perception of global motion in random-dot stimuli (Britten, Shadlen, Newsome, & Movshon, 1992; Burr & Thompson, 2011; Carrasco, 2011; Liu, Fuller, & Carrasco, 2006; Nishida, 2011; Sàenz, Buraĉas, & Boynton, 2003). Physiological evidence also shows that attention increases (and inattention decreases) neural activity for global motion in higher cortical areas such as MT (Cook & Maunsell, 2002a, b, 2004; Maunsell & Treue, 2006; Treue & Maunsell, 1996; Treue & Trujillo, 1999). On the other hand, it has been suggested that attention has little or no effect on threshold detection for local luminance motions or transients (Lee, Itti, Koch, & Braun, 1999; Lee, Koch, & Braun, 1997; Motoyoshi, 2011) and does not clearly modulate neural responses to such stimuli in primary visual cortex (Luck, Chelazzi, Hillyard, & Desimone, 1997; Moran & Desimone, 1985). These findings support the commonly held notion that attention specifically facilitates a spatially-integrated perception of visual motion.

Alternatively, recent psychophysical data suggest that the human visual system can efficiently encode ensemble image statistics with little contribution from attention (Alvarez & Oliva, 2008, 2009; Li, Rufin, Koch, & Perona, 2002). Several studies show that attention can even impair ensemble coding such as texture grouping and segmentation (Yeshurun & Carrasco, 1998, 2000). It has also been shown that attentional cuing reduces visual crowding of peripherally viewed targets (Yeshurun & Rashal, 2010). Such findings suggest that focal attention can be deleterious in cases where it refines the resolution of the visual system to a fine spatial scale that fails to integrate the coarser patterns of local elements that compose a texture. As the perception of global motion is also based on spatial integration, attention may also hinder the integration of local motion signals and thereby reduce the detection of global motion rather than enhance it.

The present study reports evidence that attending to an irrelevant letter-identification task facilitates, rather than impairs, the perception of spatially-integrated motion in a random dot display. Experiments 1 and 2 showed that limited attention reduces

Citation: Motoyoshi, I., Ishii, T., & Kamachi, M. G. (2015). Limited attention facilitates coherent motion processing. *Journal of Vision*, *15*(13):1, 1–11, doi:10.1167/15.13.1.

doi: 10.1167/15.13.1 Received March 14, 2015; published September 1, 2015 ISSN 1534-7362

behavioral thresholds for detecting coherent motion in noise but leaves contrast and velocity thresholds for local luminance motion detection largely unaffected. Experiment 3 revealed that limited attention elevates thresholds for detecting spatial variations in motion direction embedded in a field of otherwise uniform motion. Lastly, Experiment 4 found that limited attention categorically flips a motion-induced percept of direction repulsion into a percept of direction assimilation. Two additional tests confirmed that the secondary task does not enhance motion sensitivity when the motion stimulus is presented peripherally (Experiment 5) or when the attentional load of the other task is high (Experiment 6). Together, these results support the conclusion that poor attention promotes the spatial integration of local motion signals. We interpret the results in terms of a dynamic attentional modulation of the center-surround receptive field structure of high-level motion mechanisms.

Experiment 1: Detection of global motion

We first tested how behavioral detection thresholds for coherent motion in random-dot kinematograms (RDKs) are affected by attending to rapid serial visual presentations (RSVPs) of centrally presented letters.

Methods

Apparatus

Visual stimuli were presented on a CRT monitor (Mitsubishi RDF223H at Kogakuin University, Sony GDM520 at NTT CS Labs) controlled by a graphics card (CRS ViSaGe). The CRT had a frame rate of 60 Hz and a pixel resolution of 0.04°/pixel. Each pixel had eight-bit depth, and the overall contrast was controlled by a 14-bit lookup table. The mean luminance of the monitor was 42.0 (at Kogakuin University; 15 observers) or 52.0 cd/m^2 (at NTT CS Labs.; four observers).

Observers

Nine paid volunteers and one of the authors (TI) participated in the experiments. All observers except TI were naive to the purpose of the experiment, and all had little or no prior experience in viewing random-dot kinematograms. All participants had normal or corrected-to-normal vision. All experiments followed the Declaration of Helsinki guidelines, and all participants provided informed consent.

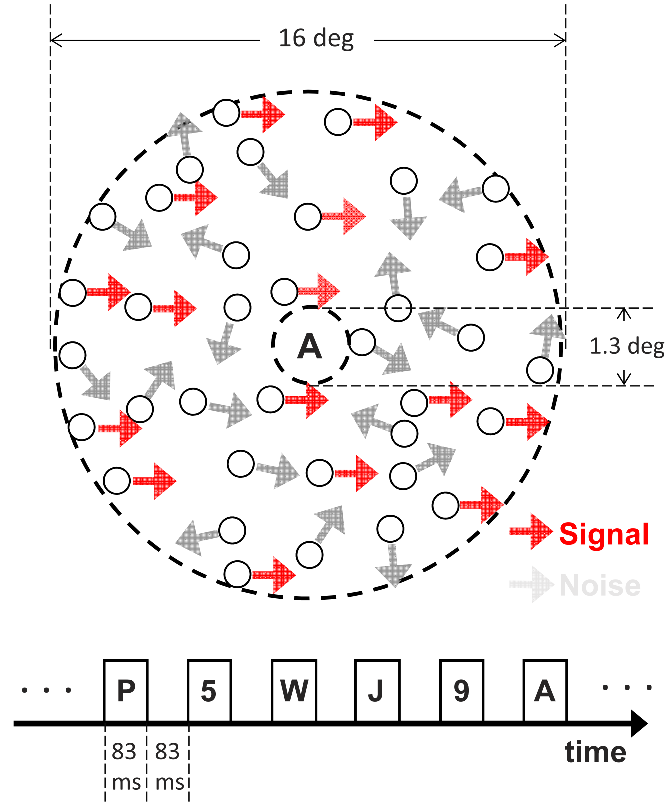

Figure 1. Schematic diagram of a stochastic motion display. Signal dots moved coherently among randomly moving noise dots. A rapid stream of letters was presented in the center.

Stimuli

Stimuli consisted of circular random-dot kinematograms (RDKs) composed of bright dots presented on a uniform gray background of 40 (H) × 30 (W) deg (Figure 1). RDKs were spatially filtered by a difference-of-Gaussian (DoG) function with a center and surround *SD* of 0.06 and 0.24°. Spatial filtering limited stimulus content to a narrow spatial-frequency band and ensured that results ultimately could not be attributed to changes in the spatial-frequency tuning of visual contrast sensitivity. For example, increased sensitivity for detecting motion in this RDK, which does not contain low spatial frequencies, cannot be attributed to an increased sensitivity to image contrast at those spatial frequencies. Dot position was controlled with 1/20 subpixel accuracy to ensure proper display under very slow motion conditions. For every frame of the 60 Hz refresh, a new set of dots appeared at random positions within the field and these dots moved with a constant velocity for a "lifetime" period of 217 ms. A proportion of dots moved coherently toward the left or right, and the remaining noise dots moved in random directions. The center of the RDKs was masked by a uniform gray patch of 1.3° in diameter, and small black letters (0.5 × 0.5°, Arial font) were presented sequentially (rapid serial visual presentation; RSVP). The RSVP stream contained random alphabet letters (except O, I, Q, Y, Z) as well as two digits with values randomly chosen between 1 and 9. Each letter was presented for 83 ms and was followed by a blank interval of 83 ms.

In the standard condition, the field size of the RDKs was 16° in diameter, dot density was 400 dots/frame, motion velocity was 2.4°/s, and luminance contrast (Lmax/Lmean −1) was set at 0.8. One of these parameters was varied in turn across conditions; size was varied between 7.9 and 23.6° (five observers), density varied between 50 and 400 dots / frame (five observers), velocity varied between 1.2 and 4.7°/s (six observers), and contrast varied between 0.05 and 0.8 (seven observers).

Procedure

On each trial, the RSVP stream was shown for 1 s, and the RDK was presented for 217 ms at the midpoint of that period. Observers participated in two different sessions and the order of sessions was counterbalanced across observers. In single-task sessions, observers were asked to indicate the direction of the RDK's coherent motion while fixating the central display of RSVP letters. Responses were made by pressing a button. In dual-task sessions, observers first pressed buttons to report the two digits contained in the RSVP stream in the correct order. If the observers successfully identified the digits, they then indicated the motion direction of the RDK. If they failed to identify the digits, a feedback tone was given and the motion judgment was skipped. The observers were instructed to keep a performance of more than 90% correct in the RSVP task. Data for observers who could not reach for this criterion were not used in the analysis. No feedback was given to responses on the RDK motion task.

For both the single- and dual-task sessions, we used a staircase method to measure the threshold proportion of signal dots required to correctly discriminate the direction of coherent motion. A single measurement session started with an RDK composed of 100% signal dots. We confirmed that all subjects showed virtually 100% correct performance at this level in both task modes, and we assumed there was no lapse rate in the psychometric function. Signal proportion was decreased by 0.2 log units after three successive correct responses and increased by the same amount after one incorrect response. Different staircases assigned to each stimulus condition were randomly interleaved across trials. Sessions were terminated when all staircases exceeded 20 trials. Measurements were repeated until the total number of trials exceeded 200 in each condition. Proportion-correct data were modeled by maximum-likelihood logistic function fits and coherence thresholds were estimated as signal proportions corresponding to 86% correct (a d-prime value of 1.5). The standard error of thresholds estimated for individual observers by using a bootstrap method (5,000 samples) was 0.15 log unit on average, thereby indicating that threshold estimation was stable. Coherence sensitivity was defined as the inverse of the threshold. Proportion correct for the RSVP digits was 97% on average and showed no systematic variations across stimulus conditions.

Results

Each panel in Figure 2 shows coherence sensitivity (the inverse of coherence threshold) obtained for various dot densities (Figure 2a), RDK sizes (Figure 2b), luminance contrasts (Figure 2c), and dot velocities (Figure 2d). For a range of conditions, we found that sensitivity is higher under dual-task conditions (red circles) than under single-task conditions (blue squares) by up to ∼50%. Asterisks on data points denote statistical significance for differences between the task modes; *t* test on a log scale (uncorrected). A higher sensitivity under the dual-task condition was found consistently across data from individual observers.

Experiment 2: Detection of local motion

Improvements in coherence sensitivity with reduced attention could be due to increased sensitivity to local dot motions resulting from an increase in motion sensor gain and/or from reduced eye motion due to fixation of the RSVP letters. A recent study showed that exogenous attentional cueing impairs the perception of apparent motion between successively flashed stimuli (Yeshurun & Hein, 2011). However, if such mechanisms mediate improvements for coherence sensitivity, the dual task should also improve sensitivities for local motion signals. To test this latter hypothesis, we measured the minimum luminance-contrast and dot-velocity thresholds required for detecting motion in a perfectly coherent RDK.

Methods

We used RDKs composed of signal dots only and measured the minimum luminance-contrast and velocity thresholds required to discriminate the RDK's direction of motion. For luminance contrast thresholds, the contrast of the whole RDK was varied in steps of 0.1 log units in accordance with the three-down-one-up staircase described above. For velocity thresholds,

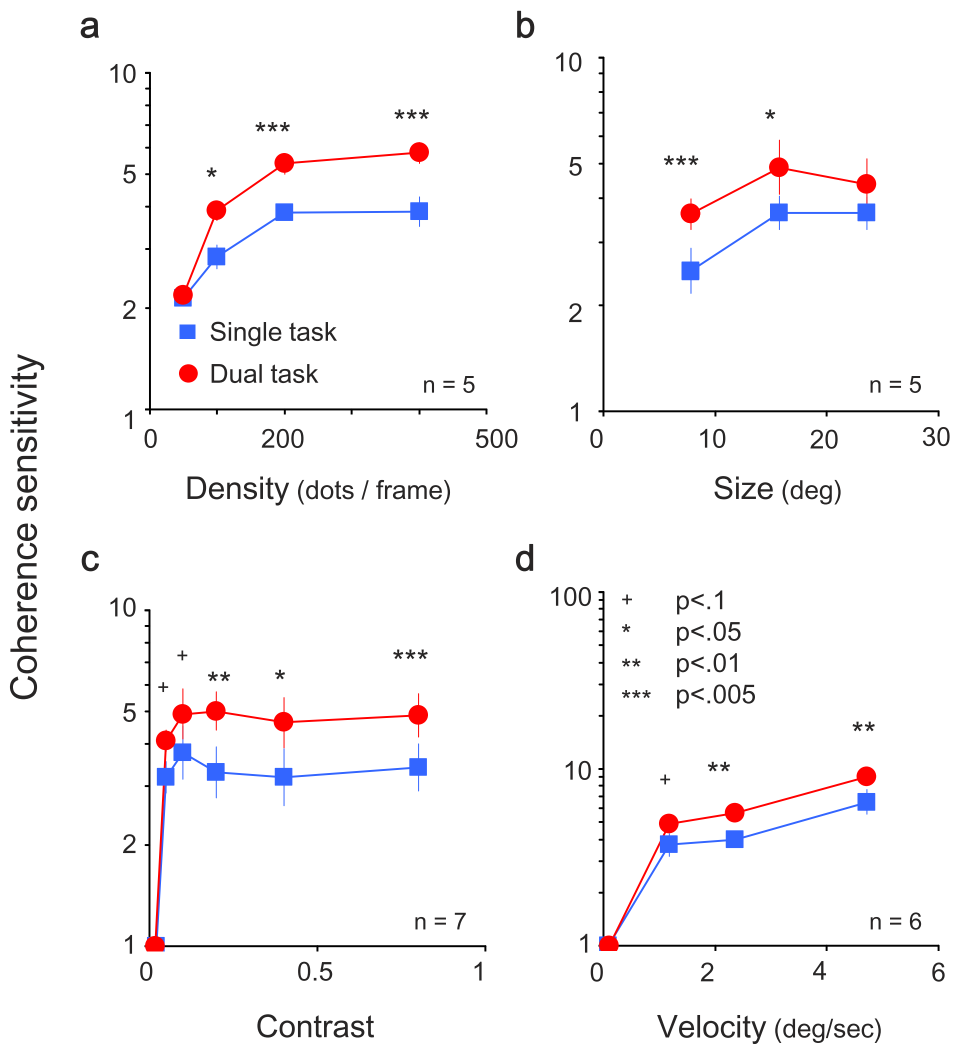

Figure 2. Experiment 1: Results. Detection sensitivities for coherent motion as observers attended either to the motion display (single task: blue squares) or concurrently to the central letters and the motion display (dual task: red circles). Panels show results for stimuli with variable (a) densities, (b) sizes, (c) contrasts, and (d) velocities. Data on the abscissa in (c) and (d) show contrast and velocity thresholds measured in Experiment 2. Error bars represent +/−1 *SEM* across observers.

dot velocity was varied by 0.2 log units with respect to the initial value of 2.4°/s. The contrast and velocity sensitivities were defined as the inverse of the thresholds respectively. Other parameters of the RDK followed the standard default condition: density = 400 dots/frame, size = 16°, contrast = 0.8, velocity = 2.4°/s. The same observers from Experiment 1 participated in the current experiment. The proportion correct for the RSVP digits was 97% on average, and other details remained the same as in Experiment 1.

Results

Figure 3 shows the contrast sensitivity (Figure 3a) and the velocity sensitivity (Figure 3b) for detecting motion direction in noiseless RDKs. We found that neither contrast nor velocity sensitivity improves under dual-task conditions, $t(5) = 0.4$, $p = 0.70$ for contrast, $t(5) = 1.6$, $p = 0.18$ for velocity; t test on a log scale). These results suggest that the improvements in coherence sensitivity with reduced attention observed in Experiment 1 reflect an enhancement of spatial motion integration rather than a sensitization to local dot motion.

Experiment 3: Detection of motion differences

A number of studies suggest that motion integration is mediated by high-level motion mechanisms with antagonistic center-surround receptive fields (Born & Bradley, 2005; Eifuku & Wurtz, 1998). These high-level

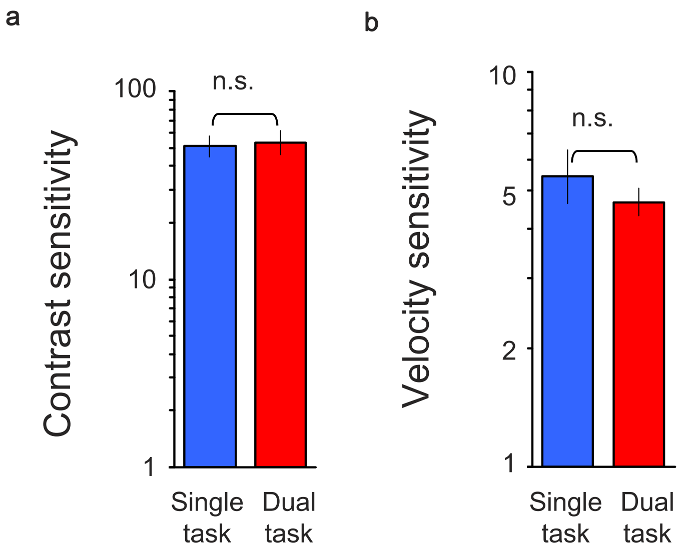

Figure 3. (a) Contrast sensitivity (the inverse of luminance-contrast threshold) for simple motion discrimination. (b) Velocity sensitivity (the inverse of minimum velocity threshold). Error bars represent +/−1 *SEM* across observers.

motion detectors strongly respond to motions that are spatially pooled within the receptive field center but are suppressed by motions that cover the receptive field surrounds. Consequently, detector response increases as motion signals covers a small area within the receptive field center but decreases as they covers a larger area including the surround. In general, the size of the spatial area covered by the center pooling region is inversely related to the strength of inhibition from the modulating surround, and this leads to the idea that reduced attention to the RDK broadens that spatial extent of motion integration via the reduction of surround inhibition. In order to test this hypothesis, we examined whether limiting attention impairs the detection of spatial variations in motion direction—a neural computation considered as an essential function of the inhibitory surround (Regan & Beverley, 1984).

Methods

RDKs were composed of dots that all moved either towards the left or towards the right on each trial. However, dots in either the left or right half of the RDK were assigned random directions according to a Gaussian distribution with a particular standard deviation (Figure 4a). If the standard deviation of direction distribution is large enough, the RDK appeared as segregated by a boundary between the noisy-direction region and the coherent-motion region.

Observers were asked to indicate which region—the left or the right—contained dots with random directions. The standard deviation of the dot-direction distribution was varied by 0.1 log units in accordance with a staircase method, and thresholds corresponding to 83% correct were estimated for the single- and dual-task modes. Sensitivity to direction differences was defined as the inverse of threshold. The RDK parameters used in the experiment followed those in the standard condition: density = 400 dots/frame, size = 16°, contrast = 0.8, velocity = 2.4°/s. Six observers

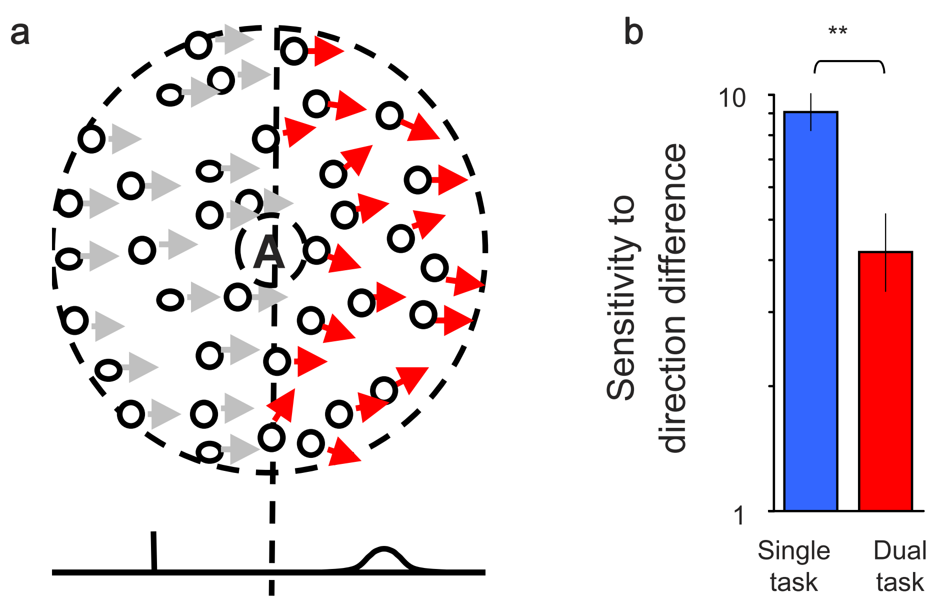

Figure 4. (a) Schematic diagram of the RDK used in Experiment 3. Dots in a half region (gray) moved coherently in a constant direction while dots in the other region (red) also moved in a common global direction but where local directions were corrupted by Gaussian noise. Observers indicated the perceived direction of the noisy half. (b) Sensitivity for detecting spatial variations in motion direction. Error bars represent +/−1 *SEM* across observers.

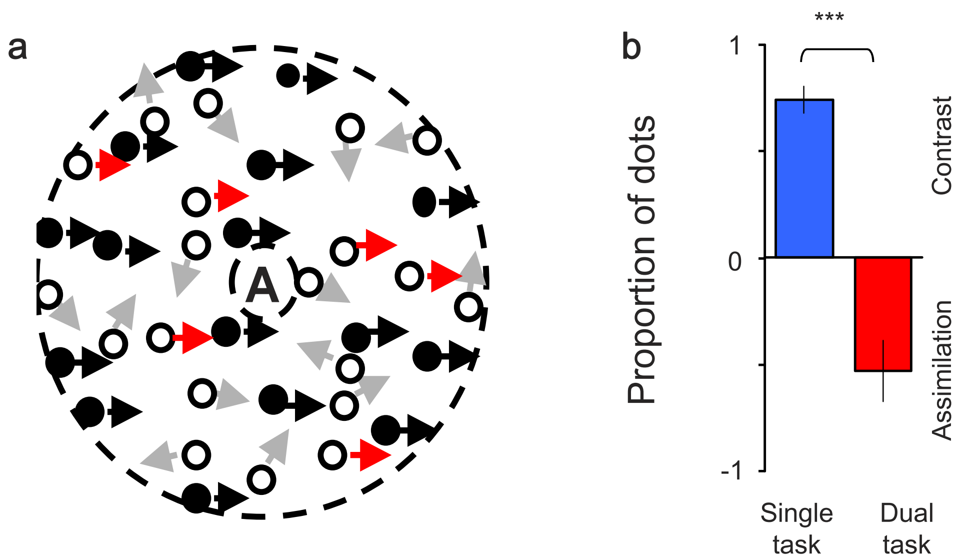

Figure 5. (a) Schematic diagram of the RDK used in Experiment 4. The RDK consisted of an equal proportion (1:1) of black and white dots. All black dots moved coherently either left or right, but only a proportion of white dots moved coherently while the remaining white dots moved in random directions. Observers indicated the perceived direction of white dots. (b) Proportion of white dots required to cancel the illusory motion elicited by inducing black dots. Error bars represent +/−1 *SEM* across observers.

participated in the experiment. The proportion correct for the RSVP digits were 95% on average. Other details were the same as in Experiment 1.

Results

Figure 4b shows the results. Sensitivity for detecting spatial variations in motion direction was profoundly reduced for the dual task, $t(5) = 4.3$, $p < 0.01$. This finding is consistent with the notion that poor attention reduces surround inhibition in the receptive field of high-level motion mechanisms.

Experiment 4: Apparent motion induction

A striking perceptual consequence of center-surround receptive field interactions is known as illusory motion contrast—a phenomenon wherein neighboring moving dots are perceptually repelled from each other (Tynan & Sekuler, 1975). In Experiment 4, we leveraged this illusion to test the hypothesis that poor attention would reduce surround inhibition and consequently broaden spatial pooling. A larger pooling area, in turn, would be expected to weaken motion contrast and even potentially give rise to a percept of motion assimilation in which the directions of neighboring dots are integrated rather than repelled.

Methods

RDKs consisted of black and white dots (Figure 5a). White dots consisted of the same DoG patches as before and the black dots consisted of DoG patches with reversed contrast polarity. All dots were assigned random positions, and black and white dots had equal population numbers (1:1 ratio). In these composite RDKs, all black dots moved coherently either left or right, but only a proportion of white dots moved coherently as the remaining white dots moved in random directions. The coherence of white dots was manipulated along a bipolar spectrum analogous to the one used by Murakami & Shimojo (1996). If RDK coherence was positive, a proportion of white dots moved in the same direction as black dots. Conversely, if RDK coherence was negative, coherent white dots moved in the opposite direction of black dots. At zero coherence, all white dots moved in random directions. On each trial, an RDK with a particular coherence (from −1 to +1) was presented and observers indicated whether white dots appeared to move either left or right. We measured the coherence of white dots that canceled the bias in overall perceived motion by means of a staircase method. Coherence decreased by 0.2 if observers indicated that white dots moved in the same direction as the black dots and increased by the same amount when observers indicated the opposite direction. After sessions were completed, the coherence value corresponding to a 50% response level was estimated by fitting a logistic function to the data. Specification of the RDK followed those of the standard condition: density = 400 dots/frame, size =

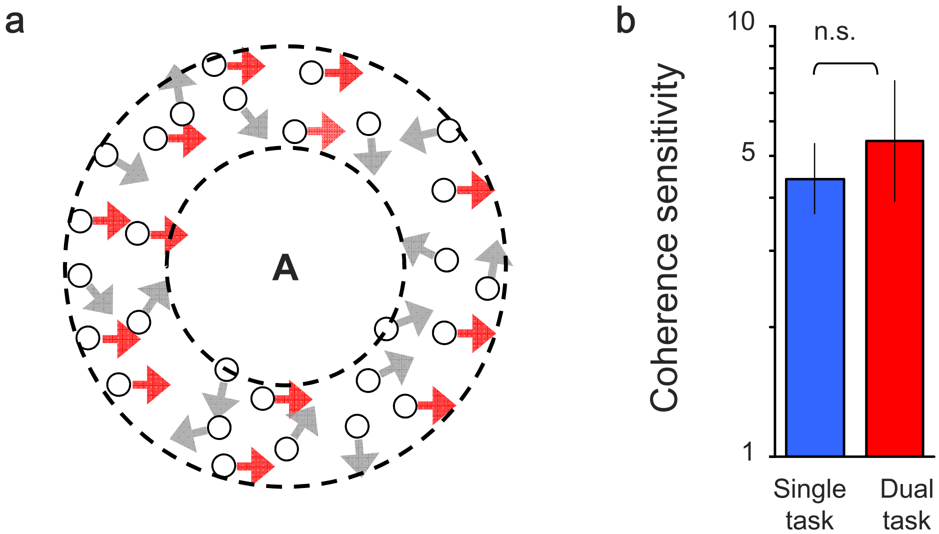

Figure 6. (a) Schematic diagram of the RDK in Experiment 5. The central part of the RDK was removed. (b) Detection sensitivities for coherent motion for the single-task condition (blue bar) and for the dual-task condition (red bar). Error bars represent +/−1 *SEM* across observers.

16°, contrast = 0.8, velocity = 2.4°/s. Five observers participated the experiment. Other details were the same as in Experiment 1. The proportion correct for the RSVP digits was 97% on average.

Results

Figure 5b shows the proportion of moving dots required to cancel the illusory motion elicited by inducing dots. The data indicate a strong motion contrast under single-task conditions (positive value) and motion assimilation in dual-task conditions. The dual task not only weakens motion contrast but categorically shifts the percept to one of assimilation, $t(4) = 11.6$, $p < 0.0005$. This line of evidence is consistent with notions that limiting attention reduces surround inhibition and broadens the spatial pooling area of high-level motion mechanisms.

Experiment 5: Peripheral stimulation

The paradoxical improvement of motion detection by inattention and corresponding changes in appearance are inconsistent with previous findings reporting either impairments or noneffects in tasks directing attention towards irrelevant stimuli (Braun & Julesz, 1998; Braun & Sagi, 1990; Lee et al., 1999; Lee et al., 1997; Pastukhov & Braun, 2007). One critical element in the current study is that stimuli were presented in the central visual field whereas stimuli are typically presented in the visual periphery in most other studies. To better assess the importance of central versus peripheral viewing, we examined sensitivity for coherent motion by using an annular RDK that only stimulates the peripheral visual field.

Methods

We measured coherence sensitivity by using a large RDK (30°) whose central area (18°) was removed (Figure 6a). The other RDK parameters used in the experiment followed those in the standard condition: density = 400 dots/frame, contrast = 0.8, velocity = 2.4°/s. Eight observers participated in the experiment. The proportion correct for the RSVP digits was 96% on average. Other details remained the same as in Experiment 1.

Results

Figure 6b shows coherence sensitivity for single and dual tasks. Although coherence sensitivity appears somewhat higher in the dual-task condition, analyses show that the dual task has no significant effect on performance, $t(7) = 1.8$, $p = 0.12$. These results are consistent with most previous studies using peripheral motion stimuli (Braun & Julesz, 1998; Braun & Sagi, 1990; Lee et al., 1999; Lee et al., 1997). The results are also consistent with the hypothesis that poor attention broadens the spatial extent of motion integration via the reduction of surround inhibition. Because the receptive fields of visual units are already large in the periphery, there is little more that inattention could do

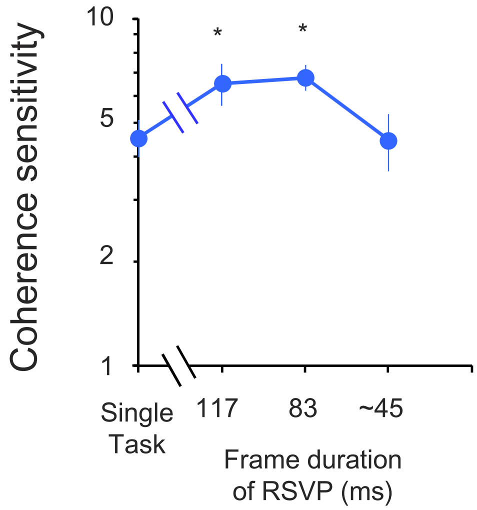

Figure 7. Detection sensitivities for coherent motion under single-task (left end) and dual-task conditions for different letter frame durations in the central RSVP task. Shorter frame durations correspond to increasingly rapid letter presentations. Error bars represent +/−1 *SEM* across observers.

to further facilitate spatial integration in peripheral viewing.

Experiment 6: Attentional load

We adjusted the rate of presentation of digits in the RSVP task so that observers felt they could still attend to the RDKs. It is interesting to test whether the sensitivity to coherent motion would still be improved even when the attentional load of the RSVP task is increased by increasing the rate of presentation of the digits in the central RSVP display.

Methods

We used the RDK from the standard condition in Experiment 1 (density = 400 dots/frame, size = 16°, contrast = 0.8, velocity = 2.4°/s.). The frame duration of each letter (and blank interval) in the central RSVP display was varied from 117, 83, and 33 to 67 ms. The duration of 83 ms corresponds to those used in Experiments 1, 2, 3, 4, and 5. The shortest duration was determined as the minimum duration at which each of seven observers could reliably perform the letter-identification task (33 ms for three observers, 50 ms for three observers, and 67 ms for one observer: 45 ms on average). At these rates, observers felt they had to extensively focus attention on the central letter stream. In separate sessions, coherence thresholds for motion detection were measured for single-task and dual-task conditions under three different RSVP rate regimes. Other details remained the same as in Experiment 1. Proportion correct for the RSVP digits at the shortest duration (~45 ms) was 90% on average, which was significantly lower than those for durations of 117 ms (96%, $t[6] = 4.0$, $p < 0.01$) and of 83 ms (96%, $t[6] = 5.1$, $p < 0.005$). These results are consistent with the notion that shorter frame duration indeed increases the observer's attentional load for the central RSVP task.

Results

Figure 7 shows the coherence sensitivity for the single and dual tasks. When the RSVP stream was relatively slow (117 and 83 ms durations), sensitivity for coherent motion detection was significantly improved by engaging in the dual task, $t(6) = 2.6$, $p < 0.05$ for 117 ms, $t(6) = 3.4$, $p < 0.05$ for 83 ms. When the RSVP was very rapid (~45 ms), however, sensitivity did not significantly improve, $t(6) = 0.06$, $p = 0.95$. These data are consistent with the notion that coherent motion detection is improved only when the attentional load of the secondary task is relatively low. However, it is also possible that the reduction in performance for the fastest RSVP is affected by to the temporal characteristics of the RSVP display. Further investigations would be needed in order to understand the implications this nonmonotonic effect for theories of attention. Nevertheless, the data indicate that the main results of the present study—the improvement in RDK performance with reduced attention—are dependent on the rate of presentation of the RSVP display and suggest that taking too much attention away from the RDK may be harmful to performance.

Discussion

The present study demonstrates that the perception of global motion is improved when attention is allocated to a different stimulus. Results from psychophysical experiments revealed that limited attention paradoxically improves sensitivity for detecting coherent motion in a traditional random-dot display (Experiment 1) but does not affect sensitivities for detecting local dot motions (Experiment 2). Attention limitation also decreased sensitivities for detecting spatial differences in local motion directions (Experiment 3) and categorically flipped an illusory motion-induced percept of repulsion into one of assimilation (Experiment 4). Two additional experiments revealed that attentional limitation does not enhance motion sensitivity if stimuli are shown in peripheral vision (Experiment 5) and if the central RSVP is very rapid

(Experiment 6). Taken together, evidence from the current study support the hypothesis that limited attention facilitates the spatial integration of local motion signals.

The present results are consistent with other lines of evidence that attention can sharpen the spatial resolution of the visual system and consequently impair performance on tasks (e.g., texture segregation) that require spatial grouping of local pattern signals (Yeshurun & Carrasco, 1998, 2000). The results are also consistent with findings that attentional cueing improves the recognition of local target in crowded displays (Yeshurun & Rashal, 2010). Whereas previous studies demonstrate failure of integration only for involuntary attention drawn by cuing stimuli, the present study demonstrates failure of integration for top-down, voluntary attention. It would be worthwhile to test in future research whether such negative effects of attention can be observed for other visual integration tasks, including the detection of Glass pattern (Wilson & Wilkinson, 1998) and the discrimination of ensemble statistics (Alvarez & Oliva, 2009), for which spatial grouping plays a fundamental role.

Pooling weak inputs over broad spatial areas is an efficient signal coding strategy with recurring implementations in biological vision, examples of which include contrast detection under scotopic light (Hood & Finkelstein, 1986) and detection of large field motion at low contrasts (Tadin, Lappin, Gilroy, & Blake, 2003). A similar mechanism may exist for integrating motion under conditions where attention is either disengaged or directed elsewhere. If lapses in attention attenuate local motion signals at some lower stage of visual processing, then such a mechanism would promote a broader spatial integration of motion signals at higher stages. However, the neural locus of these lower and higher stages is unclear. Recent studies suggest that suppression of MT activity by TMS paradoxically improves the detection of large-field motion (Tadin, Silvanto, Pascual-Leone, & Battelli, 2011) and that behavioral detection of global motion is also correlated with activities at higher areas such as VIP (Cook & Maunsell, 2002a, b). These findings lead one to postulate that disengaging attention attenuates motion coding at the level of MT but in turn promotes a broader spatial integration in cortical areas beyond MT. While speculative, these ideas nonetheless offer concrete hypotheses that could be directly tested in future physiological studies.

Recently, fruitful collaborations combining visual psychophysics and clinical psychology have uncovered perceptual correlations among individual differences and clinical populations including schizophrenia and autism (Butler, Silverstein, & Dakin, 2008; Dakin & Frith, 2005). Interestingly, some of these studies have reported that performance for detecting large-field motion is better among schizophrenic patients than normal controls (Chen, Norton, & Ongur, 2008; but see, Chen, 2011), increases with age (Betts, Taylor, Sekuler, & Bennett, 2005; Karas & McKendrick, 2009), and decreases with IQ (Melnick, Harrison, Park, Bennetto, & Tadin, 2013). These counterintuitive improvements have been attributed to reduced surround suppression in motion detectors, but the origin of this reduced suppression has remained unclear. Results from the present study offer a dynamic and parsimonious account of these varied findings as superior sensitivities for large field motion and reduced surround suppression in some populations may arise partly from deficits or individual differences in the use of attentional resources for external stimuli.

Keywords: motion, integration, attention, coherence

Acknowledgments

This study was partially supported by JSPS KAKENHI 24530921 to MGK, and by JSPS KAKENHI 26119508 and 15H03461 to IM. The data were collected when IM worked for NTT CS Labs. A part of the study was presented at annual meetings of Japanese Psychonomic Society (2012), Vision Society of Japan (2013), and Vision Sciences Society (2013).

Commercial relationships: none.
Corresponding author: Isamu Motoyoshi.
Email: imotoyosi.ac@gmail.com.
Address: Department of Life Sciences, The University of Tokyo, Tokyo, Japan.

References

Alvarez, G. A., & Oliva, A. (2008). The representation of simple ensemble visual features outside the focus of attention: Research article. *Psychological Science, 19,* 392–398.

Alvarez, G. A., & Oliva, A. (2009). Spatial ensemble statistics are efficient codes that can be represented with reduced attention. *Proceedings of the National Academy of Sciences of the United States of America, 106,* 7345–7350.

Betts, L. R., Taylor, C. P., Sekuler, A. B., & Bennett, P. J. (2005). Aging reduces center-surround antagonism in visual motion processing. *Neuron, 45,* 361–366.

Born, R. T., & Bradley, D. C. (2005). Structure and function of visual area MT. *Annual Review of Neuroscience, 28,* 157–189.

Braun, J., & Julesz, B. (1998). Withdrawing attention at little or no cost: Detection and discrimination tasks. *Perception & Psychophysics, 60,* 1–23.

Braun, J., & Sagi, D. (1990). Vision outside the focus of attention. *Perception & Psychophysics, 48,* 45–58.

Britten, K. H., Shadlen, M. N., Newsome, W. T., & Movshon, J. A. (1992). The analysis of visual motion: A comparison of neuronal and psychophysical performance. *The Journal of Neuroscience, 12,* 4745–4765.

Burr, D., & Thompson, P. (2011). Motion psychophysics: 1985-2010. *Vision Research, 51,* 1431–1456.

Butler, P. D., Silverstein, S. M., & Dakin, S. C. (2008). Visual perception and its impairment in schizophrenia. *Biological Psychiatry, 64*(1), 40–47.

Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research, 51*(13), 1484–1525.

Chen, Y. (2011). Abnormal visual motion processing in schizophrenia: A review of research progress. *Schizophrenia Bulletin, 37*(4), 709–715.

Chen, Y., Norton, D., & Ongur, D. (2008). Altered center-surround motion inhibition in schizophrenia. *Biological Psychiatry, 64*(1), 74–77.

Cook, E. P., & Maunsell, J. H. (2002a). Attentional modulation of behavioral performance and neuronal responses in middle temporal and ventral intraparietal areas of macaque monkey. *The Journal of Neuroscience, 22*(5), 1994–2004.

Cook, E. P., & Maunsell, J. H. R. (2002b). Dynamics of neuronal responses in macaque MT and VIP during motion detection. *Nature Neuroscience, 5*(10), 985–994.

Cook, E. P., & Maunsell, J. H. R. (2004). Attentional modulation of motion integration of individual neurons in the middle temporal visual area. *The Journal of Neuroscience, 24*(36), 7964–7977.

Dakin, S., & Frith, U. (2005). Vagaries of visual perception in autism. *Neuron, 48*(3), 497–507.

Eifuku, S., & Wurtz, R. H. (1998). Response to motion in extrastriate area MSTl center-surround interactions. *Journal of Neurophysiology, 80*(1), 282–296.

Hood, D. C., & Finkelstein, M. A. (1986). Sensitivity to light. In K. Boff, L. Kaufman, & J. Thomas (Eds.). *Handbook of percpetion and human performance, Vol. 1: Sensory processes and perception.* New York: John Wiley and Sons.

Karas, R., & McKendrick, A. M. (2009). Aging alters surround modulation of perceived contrast. *Journal of Vision, 9*(5):11, 1–9, doi:10.1167/9.5.11. [PubMed] [Article]

Lee, D. K., Itti, L., Koch, C., & Braun, J. (1999). Attention activates winner-take-all competition among visual filters. *Nature Neuroscience, 2,* 375–381.

Lee, D. K., Koch, C., & Braun, J. (1997). Spatial vision thresholds in the near absence of attention. *Vision Research, 37,* 2409–2418.

Li, F. F., Rufin, V., Koch, C., & Perona, P. (2002). Rapid natural scene categorization in the near absence of attention. *Proceedings of the National Academy of Sciences of the United States of America, 99*(14), 9596–9601.

Liu, T., Fuller, S., & Carrasco, M. (2006). Attention alters the appearance of motion coherence. *Psychonomic Bulletin & Review, 13*(6), 1091–1096.

Luck, S. J., Chelazzi, L., Hillyard, S. A., & Desimone, R. (1997). Neural mechanisms of spatial selective attention in areas V1, V2, and V4 of macaque visual cortex. *Journal of Neurophysiology, 77*(1), 24–42.

Maunsell, J. H. R., & Treue, S. (2006). Feature-based attention in visual cortex. *Trends in Neurosciences, 29*(6), 317–322.

Melnick, M. D., Harrison, B. R., Park, S., Bennetto, L., & Tadin, D. (2013). A strong interactive link between sensory discriminations and intelligence. *Current Biology, 23*(11), 1013–1017.

Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science, 229,* 782–784.

Motoyoshi, I. (2011). Attentional modulation of temporal contrast sensitivity in human vision. *PLoS One, 6,* e19303.

Murakami, I., & Shimojo, S. (1996). Assimilation-type and contrast-type bias of motion induced by the surround in a random-dot display: evidence for center-surround antagonism. *Vision Research, 36*(22), 3629–3639.

Nishida, S. (2011). Advancement of motion psychophysics: Review 2001-2010. *Journal of Vision, 11*(5): 11, 1–53, doi:10.1167/11.5.11. [PubMed] [Article]

Pastukhov, A., & Braun, J. (2007). Perceptual reversals need no prompting by attention. *Journal of Vision, 7*(10):5, 1–17, doi:10.1167/7.10.5. [PubMed] [Article]

Raymond, J. (2000). Attentional modulation of visual motion perception. *Trends in Cognitive Sciences, 4,* 42–50.

Regan, D., & Beverley, K. I. (1984). Figure-ground segregation by motion contrast and by luminance contrast. *Journal of the Optical Society of America A, 1*(5), 433–442.

Sàenz, M., Buraĉas, G. T., & Boynton, G. M. (2003). Global feature-based attention for motion and color. *Vision Research, 43,* 629–637.

Tadin, D., Lappin, J. S., Gilroy, L. A., & Blake, R. (2003). Perceptual consequences of centre-surround antagonism in visual motion processing. *Nature, 424,* 312–315.

Tadin, D., Silvanto, J., Pascual-Leone, A., & Battelli, L. (2011). Improved motion perception and impaired spatial suppression following disruption of cortical area MT/V5. *The Journal of Neuroscience, 31*(4), 1279–1283.

Treue, S., & Maunsell, J. (1996). Attention modulation of visual motion processing in cortical areas MT and MST. *Nature, 382,* 539–541.

Treue, S., & Trujillo, J. C. M. (1999). Feature-based attention influences motion processing gain in macaque visual cortex. *Nature, 399,* 575–599.

Tynan, P., & Sekuler, R. (1975). Simultaneous motion contrast: Velocity, sensitivity and depth response. *Vision Research, 15,* 1231–1238.

Wilson, H. R., & Wilkinson, F. (1998). Detection of global structure in Glass patterns: Implications for form vision. *Vision Research, 38,* 2933–2947.

Yeshurun, Y., & Carrasco, M. (1998). Attention improves or impairs visual performance by enhancing spatial resolution. *Nature, 396*(6706), 72–75.

Yeshurun, Y., & Carrasco, M. (2000). The locus of attentional effects in texture segmentation. *Nature Neuroscience, 3*(6), 622–627.

Yeshurun, Y., & Hein, E. (2011). Transient attention degrades perceived apparent motion. *Perception, 40,* 905–918.

Yeshurun, Y., & Rashal, E. (2010). Precueing attention to the target location diminishes crowding and reduces the critical distance. *Journal of Vision, 10*(10):16, 1–12, doi:10.1167/10.10.16. [PubMed] [Article]