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Eccentricity Effects on the Efficiency of Attentional Networks: Evidence From a Modified Attention Network Test

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Abstract

The effects of eccentricity on the attentional modulation of visual discrimination have been widely studied; however, the substrate of this complex phenomenon is poorly understood. Here, we provided a measure of the effects of eccentricity on three attentional networks: alerting,

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orienting, and executive attention. Participants ($N = 63$) were tested with a modified attention network test that included an additional eccentricity variation; this test allowed us to investigate the efficiency of the attentional networks at near and far eccentricities. Compared with targets at the near eccentricity, targets at the far eccentricity generally elicited significantly longer reaction times. We also found the far eccentricity was associated with smaller orienting effect scores and larger executive control scores than the near eccentricity. Interestingly, at the near eccentricity, executive control scores were larger when the spatial information was neutral (no cue, center cue, and double cue), but at the far eccentricity, the scores were larger when the spatial information was valid (spatial cue). We propose that the allocation of attentional resources differed among these cue conditions and influenced the interference caused by conflicting information.

Keywords
attention, attentional networks, attention network test, eccentricity

Introduction

Previous studies have clearly demonstrated that attention encompasses multiple functions (Posner & Petersen, 1990; Posner & Rothbart, 2006). According to the attention network approach, the human attentional system can be subdivided into three functionally and anatomically independent networks—alerting, orienting, and executive control (Fan, McCandliss, Sommer, Raz, & Posner, 2002). Alerting refers to the ability to achieve and maintain an alert state and facilitates response readiness in preparation for an incoming stimulus. Orienting is defined as the ability to select and shift attention to the location of an incoming stimulus, and executive control is often used to describe a set of more complex abilities that include the detection and resolution of conflict among the various computations used to control thoughts or behaviors.

Fan et al. (2002) developed an attention network test (ANT) that provides a measure of the efficiency of these three attentional networks. The test combines the Eriksen flanker task (Eriksen & Eriksen, 1974) and Posner's cuing task (Posner, 1980) to differentiate independent attention components in a single paradigm. The ANT is widely used to study attentional performance (Raz & Buhle, 2006). Moreover, the results of several ANT studies have indicated that the three attentional networks also interact and integrate with each other (Fan et al., 2009; Spagna et al., 2014).

A large body of evidence suggests that our ability to discriminate among visual stimuli is not uniform throughout the visual field and that it decreases with increasing eccentricity (Carrasco, Evert, Chang, & Katz, 1995; Zahabi & Arguin, 2014). Electrophysiological data from the primary visual cortex indicate that many aspects of spatiotemporal computations are remarkably similar across the visual field, although subtle variations are detectable; these observations suggest that visual processing in the peripheral visual field is likely to involve a distinct network of specialized cortical areas (Yu, Chaplin, & Rosa, 2015). One study showed that the perceived magnitude of changes in naturalistic scenes was lower for peripheral than for foveal viewing (To, Gilchrist, Troscianko, & Tolhurst, 2011), and another audiovisual interaction study suggested that the eccentricity of visual stimuli affects audiovisual interactions in a visual attention task (Wu, Li, Bai, & Touge, 2009). The allocation of attentional resources likely varies based on eccentricity, and such differences in allocation also likely influence the function of attention. Generally, the allocation of attentional resources diminishes as eccentricity increases (Carrasco, Giordano, & McElree, 2006; Carrasco, Talgar, & Cameron, 2001; Yao, Gao, Yan, & Li, 2011), consistent with the relationship between eccentricity and visual perception. Attention improves perception and enhances neural responses to visual stimuli at attended locations, and the magnitude of the attentional enhancement increases with eccentricity (Carrasco et al., 2006; Carrasco & Yeshurun, 2009; Yeshurun & Carrasco, 1999). Another study that used a texture segmentation task showed that attention increased visual resolution and improved performance at far eccentricities and worsened resolution and performance at near eccentricities (Yeshurun & Carrasco, 1998, 2000). In addition, the allocation of attentional resources might affect the function of attention. For example, a series of studies have indicated that devoting more attentional resources to conflicting information creates more interference (Chen, Wei, & Zhou, 2006; Yeshurun & Levy, 2003). Although the ANT has been widely used to study attentional functions, relatively little is known about whether the eccentricity of a target can modulate the efficiency of attentional networks.

In the present study, we aimed to assess whether eccentricity can affect the efficiency of attentional networks. In particular, we developed a modified ANT in which cue stimuli and target arrows were located at two levels of eccentricity.

Methods

Participants

Sixty-three graduate students (30 males and 33 females) participated in the study. All of the subjects were right-handed and had normal or corrected-to-normal vision and no history of neurological disorder. The experiment was approved by the ethics committee of Shanxi Medical University and was conducted with the understanding and written consent of each participant.

Apparatus

Stimuli were presented via Presentation (Neurobehavioral Systems, Inc., Albany CA) on a ThinkPad personal computer running Windows 8. The stimuli were presented on a 15$''$ MAG X3770 monitor with a refresh rate of 60 Hz and a resolution of 1366×768 pixels. The participants viewed the screen from a distance of 75 cm, and the responses were collected unimanually from a computer keyboard placed in front of the subject.

Stimuli

The efficiency of the alerting, orienting, and executive networks was assessed using a modified version of the ANT originally developed by Fan et al. (2002). As shown in Figure 1(a), the flanker target stimuli for the ANT consisted of a row of five horizontal black lines with arrowheads pointing leftward or rightward, presented against a gray background. These targets were flanked on either side by two arrows oriented in either the same direction (congruent condition) or the opposite direction (incongruent condition) or by lines without arrowheads (neutral condition). A single arrow or line subtended 0.58° of visual angle, and the contours of adjacent arrows or lines were separated by 0.06° of visual angle. Thus, the stimuli (one central arrow plus four flankers) subtended a total of 3.27° of visual angle. To investigate the effect of eccentricity on the efficiency of the attentional networks, the targets were plotted in near and far space, at 1.08° or 5.4°, respectively, above or below the fixation point (Figure 1(c)).

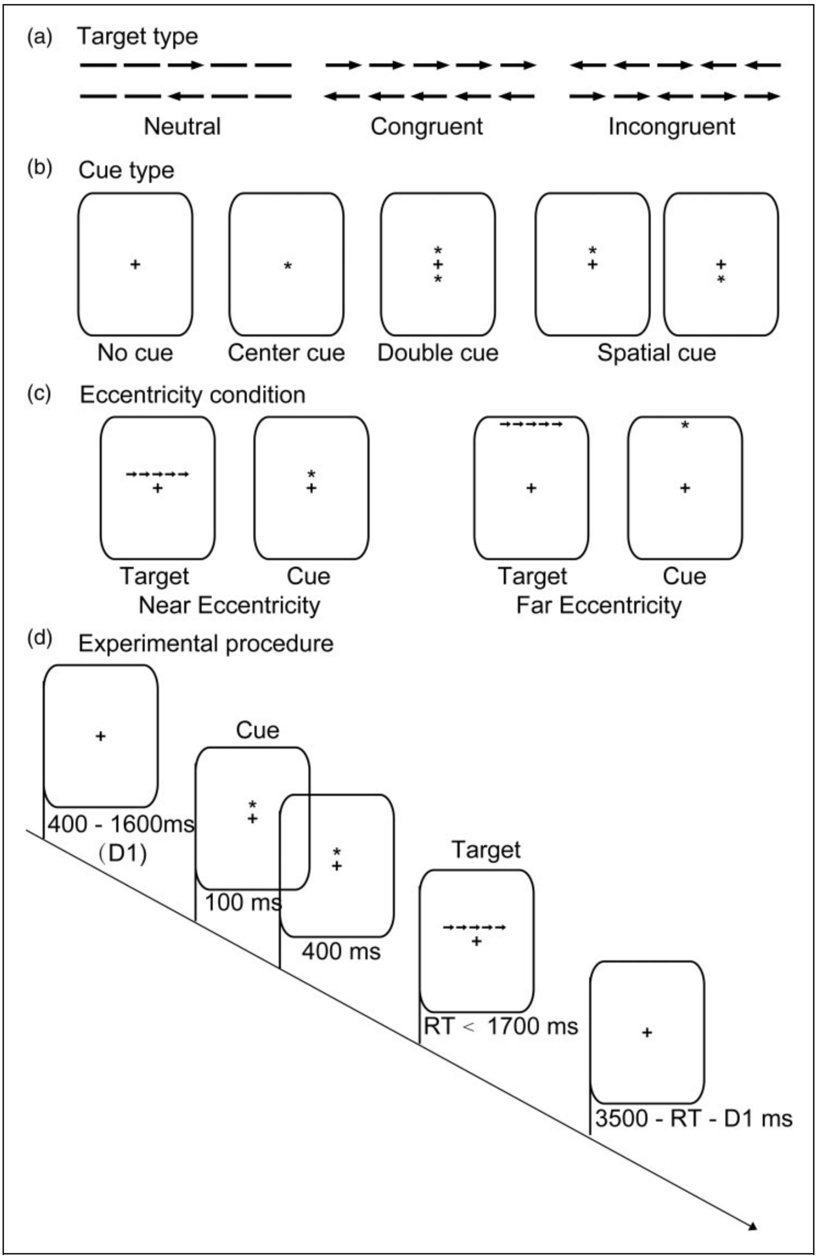

Figure 1. Experimental paradigm of the ANT. (a) The six target stimuli used in the experiment. (b) The four cue conditions. The double cues and spatial cues were presented at the near eccentricity. (c) Examples of targets and cues at the near and far eccentricity, at 1.05° and 5.4°, respectively, of visual angle above the fixation point. (d) Example of the procedure.

The targets were preceded by one of four types of cues: no cue, center cue, double cue, or a spatial cue (Figure 1(b)). In the no cue condition, the participants saw only a fixation cross for 100 ms. In the center cue condition, the participants were presented an asterisk at the location of the center fixation cross. In the double cue condition, there were two asterisks corresponding to the two possible target locations, up and down. In the spatial cue condition, the cue was located at the position of the target. The double and spatial cues were located at near and far positions (1.08° or 5.4° of visual angle from the point of fixation), consistent with the eccentricity positions of the targets and flankers.

Each trial consisted of five events (Figure 1(d)). First, there was a fixation period for a randomly varied duration (400–1600 ms). Then, a cue was presented for 100 ms. There was a short fixation period for 400 ms after the cue, and then the target and flankers appeared simultaneously. The target and flankers were presented until the participant responded, for a maximum of 1700 ms. After the participants made a response, the target disappeared immediately, and there was a post-target fixation period for a variable interval that was based on the duration of the first fixation and the reaction times (RTs; 3500 ms minus the duration of the first fixation minus the RT). After this interval, the next trial began. Each trial lasted for 4000 ms. The fixation cross remained at the center of the screen throughout the whole trial.

Design

In the present study, we aimed to compare behavioral performance on the ANT when the cues and flanker target stimuli were located at two levels of eccentricity (1.08° and 5.4°). Thus, the experiment followed a $4 \times 3 \times 2$ factorial design with a cue condition (no cue, center cue, double cue, or spatial cue), flanker condition (neutral, congruent, or incongruent), and eccentricity condition (near or far/1.08° or 5.4° of visual angle).

Procedure

The experiment consisted of a 24-trial, full-feedback practice block and six 96-trial experimental blocks with no feedback. Each experimental block consisted of 96 trials (4 Cue Conditions $\times$ 2 Target Locations $\times$ 2 Target Directions $\times$ 3 Flanker Conditions $\times$ 2 Eccentricity Positions). The trials were presented in a random order. The practice block lasted approximately 2 minutes, while each experimental block lasted approximately 6 minutes. Between blocks, the participants were allowed a short break period to rest their eyes. The total experiment lasted approximately 1 hour.

The participants' task was to identify the direction of the centrally presented arrow and to indicate their response by pressing keys on a computer keyboard with their right hand. The participants were instructed to focus on the fixation point throughout the task and to respond as quickly and accurately as possible. The responses were made by pressing the left-arrow key for left-arrow targets and the right-arrow key for right-arrow targets.

According to the reports of Fan, eye movements do not influence the ANT (Fan et al., 2002). As an additional eccentricity variation, we monitored the eye movements of 10 subjects throughout the task. Eye position was recorded and analyzed using eye tracking glasses from Senso Motoric Instruments (SMI) with a sampling rate of 60 Hz. The experimenter observed the eye-position display in real time to ensure that the subjects maintained central fixation. We also ran a few subjects without instructing them to maintain fixation. When the subjects were instructed to maintain fixation, eye movements were relatively rare. When this instruction was not given, eye movements were very common.

Attentional Network Definitions and Data Analysis

The original ANT proposed by Fan et al. used differences in the RTs for the different conditions to measure the alerting, orienting, and executive control networks. In this task, presenting stimuli with different eccentricities might produce eccentricity effects that reflect differences in the efficiency of attention and in perceptual factors between near and far eccentricities. To eliminate the influence of perceptual factors, the ratio effect scores for each eccentricity were scaled as a percentage of the baseline condition as shown later.

$$\text{Alerting} = \left(\frac{RT_{no\ cue} - RT_{double\ cue}}{RT_{double\ cue}}\right) \times 100\%$$

$$\text{Orienting} = \left(\frac{RT_{center\ cue} - RT_{spatial\ cue}}{RT_{spatial\ cue}}\right) \times 100\%$$

$$\text{Executive control} = \left(\frac{RT_{incongruent} - RT_{congruent}}{RT_{congruent}}\right) \times 100\%$$

We carried out repeated-measures analysis of variance for the RTs and the attentional network scores. To examine the mutual independence of the networks, we calculated correlations among the attentional networks when the stimuli were presented at the near and far positions. The reliability of the three attentional networks was estimated by split-half correlations between the first and second halves of the task.

Results

Response Times

Prior to analysis, trials with a RT less than 200 ms or greater than 3 standard deviations from the grand mean were excluded. This procedure excluded 0.3% of the trials in the study. Trials with errors (2.4%; $SD = 4.1$) were also excluded from the analysis. The overall mean RT for correct trials was 610 ms ($SD = 96$). Table 1 shows the mean RTs for all of the conditions.

A $4 \times 3 \times 2$ repeated-measures analysis of variance was conducted on the RTs with cue (no cue, center cue, double cue, and spatial cue), flanker (congruent, incongruent, and neutral), and eccentricity (near and far) as factors. RTs differed between the cue conditions ($F(3, 186) = 1103.2$, $p < .0001$, $\eta^2 = 0.95$); the fastest responses were observed for trials that included a spatial cue (536 ms), whereas the slowest were observed for no cue trials (667 ms).

Table 1. Mean Correct Reaction Times (ms) for All Conditions.

		None	Center	Double	Spatial
	Congruent	598.7 (71.4)	544.1 (65.7)	533.7 (57.1)	498.8 (60.6)
Central	Incongruent	673.1 (75.9)	642.3 (79.5)	625.7 (71.8)	559.7 (70.3)
	Neutral	593.6 (68.7)	539.2 (63.5)	534.0 (59.2)	492.6 (62.9)
Peripheral	Congruent	698.4 (64.7)	655.8 (61.4)	636.2 (66.6)	532.6 (65.2)
	Incongruent	756.9 (75.6)	717.5 (74.1)	699.7 (69.8)	604.3 (77.0)
	Neutral	687.5 (63.5)	649.3 (63.3)	631.2 (63.8)	531.7 (67.4)

Note. Values are listed as “mean (standard deviation).

Responses were much slower on incongruent (660 ms) than on congruent and neutral trials (586 and 582 ms), resulting in significant differences among the flanker conditions ($F(2, 124) = 734.4$, $p < .0001$, $\eta^2 = 0.92$). Responses to targets at the near eccentricity were on average 79 ms faster than those at the far eccentricity ($F(1, 62) = 1233.2$, $p < .0001$, $\eta^2 = 0.95$), and the interaction between cue and eccentricity was significant ($F(3, 186) = 147.7$, $p < .0001$, $\eta^2 = 0.7$). The results also revealed an eccentricity effect on executive control, as indicated by the interaction between flanker type and eccentricity ($F(2, 124) = 26.1$, $p < .0001$, $\eta^2 = 0.30$). Furthermore, the cue $\times$ flanker interaction was significant ($F(6, 372) = 6.77$, $p < .0001$, $\eta^2 = 0.1$), and the Cue $\times$ Flanker $\times$ Eccentricity interaction was also significant ($F(6, 372) = 13.5$, $p < .0001$, $\eta^2 = 0.18$).

Attention Network Scores

As shown in Figure 2, there was no significant difference in the alerting effect scores between the two eccentricities ($F(1, 62) = 3.29$, $p = .08$, $\eta^2 = 0.05$). The orienting effect scores for the near eccentricity were smaller than those for the far eccentricity ($F(1, 62) = 265.2$, $p < .0001$, $\eta^2 = 0.81$). The executive control scores were significantly larger when the stimuli were presented at the near eccentricity compared with when they were presented at the far eccentricity ($F(1, 62) = 72.9$, $p < .0001$, $\eta^2 = 0.54$). We confirmed that the executive control scores were influenced by cue, as indicated by the interaction between cue and eccentricity ($F(3, 186) = 33.6$, $p < .0001$, $\eta^2 = 0.35$, Figure 3). When the spatial information was neutral (no cue, center cue, and double cue), the executive control scores were larger for the near eccentricity than for the far eccentricity (all: paired t test, $t_{(62)} > 5.0$, $p < .001$); when the cue was valid (spatial cue), the executive control scores were larger when the stimuli were presented at the far eccentricity (paired t test, $t_{(62)} = 2.1$, $p = .04$).

Correlational Analyses

Before we analyzed the intranetwork correlations between the near and far positions, we conducted a between-network correlational analysis so that we could compare our findings with those of Fan et al. (2002). For the ANT scores, none of the between-network correlations was significant (Table 2). These between-network correlations are similar to those reported by

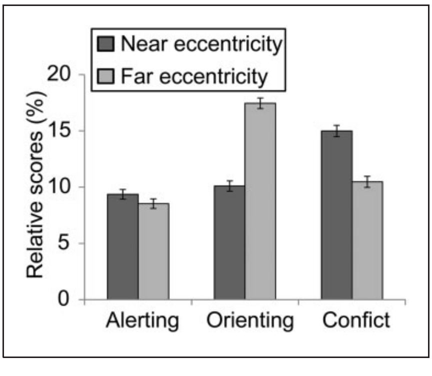

Figure 2. The relative scores for the three attentional networks for the near and far eccentricities. There was a significant difference between the near and far eccentricities for the orienting and executive control networks. The error bars represent the standard error.

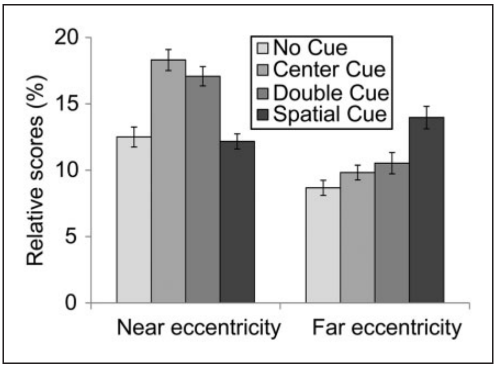

Figure 3. Executive control scores according to cue condition for the near and far eccentricities. The error bars represent the standard error.

Table 2. Correlations Between Scores of Attentional Networks.

		Over all			Near			Far		
		A	O	EC	A	O	EC	A	O	EC
Over all	A									
	O	0.06								
	EC	−0.05	0.14							
Near	A	**0.82****	−0.05	−0.07						
	O	0.02	**0.83****	0.05	−0.14					
	EC	−0.04	−0.04	**0.81****	−0.07	−0.13				
Far	A	**0.85****	0.16	−0.02	**0.41****	0.01	0.05			
	O	0.06	**0.91****	0.18	−0.01	**0.53****	0.19	0.18		
	EC	−0.03	0.25	**0.87****	0.09	0.04	**0.42****	0.08	0.25	

Note. A = alerting; O = orienting; EC = executive control scores. Significant correlations are indicated in boldface.
**$p \leq .01$.

Fan et al. (2002). We found that the values of the alerting, orienting, and conflict effects showed significant correlations between the near and far positions (Table 2).

Split-Half Correlations (Reliability of the Network Values)

To assess the reliability of the three indexes, we computed Pearson correlations for scores between the first and the second halves of the task across all subjects, as did Fan et al. (2002). The results are presented in Table 3. The reliability of the altering, orienting, and executive control scores were similar to those obtained using the original ANT (Fan et al., 2002). Importantly, for all three networks, the near ANT provided more reliable scores than the far ANT.

Discussion

This experiment presented a new version of the ANT with the additional variable of eccentricity and reliably measured the efficiency of alerting, orienting, and conflict

Table 3. Reliability of the Alerting, Orienting, and Executive Control Scores, as Measured by Split-Half Correlations.

	Over all	Central	Peripheral	ANT (Fan et al., 2002)
Alerting	**0.46****	**0.37****	**0.46****	**0.52****
Orienting	**0.64****	**0.41****	**0.57****	**0.61****
Conflict	**0.63****	**0.39****	**0.58****	**0.77****

Note. ANT = attention network test. Significant correlations are indicated in boldface.
**$p \leq .01$.

resolution at near and far eccentricities. In the present study, we confirmed that the ability to process targets at near eccentricity positions was greater than the ability to process those at far eccentricity positions, as demonstrated by faster RTs. Moreover, using the modified ANT with the additional variable of eccentricity, we could measure the efficiency of the alerting, orienting, and executive control network; these results were similar to the results of previous studies (Fan et al., 2002, 2009). Importantly, we found eccentricity effects on the orienting and executive control scores. Furthermore, the executive control score exhibited a significant interaction with cue type.

The executive control function of attention involves complex mental operations to detect and resolve conflict (Fan et al., 2002; Raz & Buhle, 2006). Similar to Fan's report (2002), we found a significant executive control score in all of the cue conditions, and this effect was influenced by cue type. For example, compared with a centrally presented cue, the presentation of a spatial cue at the target location reduced the executive control scores. More importantly, the influence of eccentricity on the executive control scores differed between the cue types. When the spatial information was neutral (no cue, center cue, and double cue), the executive control score was larger at the near eccentricity than at the far eccentricity; however, when the spatial information was valid (spatial cue), the executive control score increased at the far eccentricity. Another study that used chain-lateral Gabor stimuli with no spatial information cue reported that crowding in orientation discrimination is minimal and depends on eccentricity (Yeotikar, Khuu, Asper, & Suttle, 2011). These findings suggest that the executive control score interacted with cue type.

The allocation of attentional resources differed between the cue conditions and influenced the interference caused by conflicting information. When spatial information is neutral (no cue, center cue, and double cue), the allocation of attentional resources diminishes as eccentricity increases (Carrasco et al., 2001, 2006; Yao et al., 2011), consistent with the reduction in visual perceptual abilities that occurs as eccentricity increases. The allocation of additional attentional resources to conflicting information creates more interference (Chen et al., 2006; Yeshurun & Levy, 2003). Thus, the larger executive control scores that were observed at the near eccentricity resulted from greater flanker interference due to the allocation of additional attentional resources. In contrast, when the spatial information regarding the target is valid, attention can enhance behavioral performance. Moreover, the magnitude of the performance enhancement increases with eccentricity (Carrasco et al., 2001; Carrasco & Yeshurun, 2009; Yeshurun & Carrasco, 1999), and the enhancement of attentional resources also increases with eccentricity (Carrasco & Yeshurun, 2009; Yeshurun & Carrasco, 1999). Thus, the larger executive control scores at the far eccentricity might be due to a larger increase in attentional resources.

Orienting can be manipulated through the presentation of a cue that indicates where a person should attend by providing direction that the person should attend the cued location. In the present study, the orienting effect could be clearly distinguished from the eccentricity effect (near vs. far) because the cues changed position in only one dimension: the vertical distance from the center of the presentation screen. To eliminate the influence of the effect of eccentricity on visual perception, at each eccentricity, the attentional network scores were defined as a percentage of the baseline condition (see Methods section). We found that the orienting effect was smaller at the near eccentricity than at the far eccentricity. As retinal eccentricity increases, target discrimination requires more attention to boost the apparent stimulus contrast and clarity (Asanowicz, Marzecová, Jaśkowski, & Wolski, 2012; Carrasco, Ling, & Read, 2004), which could largely explain the observed differences in the orienting effect between the eccentricities. The increase in the orienting effect as eccentricity increased could reflect a greater need for attentional amplification when stimuli are presented at a far position. Our finding is supported by previous demonstrations that spatial cues improve observers' performance, and that the magnitude of this improvement increases with eccentricity (Carrasco & Yeshurun, 2009; Yeshurun & Carrasco, 1999).

The reliability of the networks found in the present study was generally similar to that reported by Fan. Additionally, when each eccentricity position was analyzed separately, the reliability decreased because the number of trials decreased by half; as a result, the power of the analysis was further reduced. On the other hand, the low reliabilities of the near position networks might be due to a reduction in attentional resources due to competition between the near and far positions. In addition, we also found the altering, orienting, and executive control networks showed high correlations between the near and far positions. More interestingly, the far position showed higher reliability than the near position, suggesting that the farther eccentricity required greater attentional resources. This hypothesis is also supported by previous reports (Asanowicz et al., 2012; Carrasco et al., 2004) that showed that target discrimination requires more attention as retinal eccentricity increases.

Although attentional modulation differed across the eccentricity positions in the visual field, we found significant correlations for each attentional network at both the near and far positions. The eccentricity dependence of the attentional networks is likely related to similarities in the architecture of the visual cortex involved in the networks. For example, cortical regions with near and far representations show similar angle maps, organization and functional responses but exhibit different cortical magnifications and receptive fields, according to evidence from retinotopic mapping studies (Wandell & Winawer, 2011; Wang, Yamamoto, Wu, & Ejima, 2014; Wu et al., 2012). The substrates associated with the attentional networks overlap greatly at the near and far positions, which may argue that these networks depend on differences in the encoding of the visual field across eccentricities.

Conclusion

In the present study, we examined the effect of eccentricity on attentional networks using a modified ANT. We found eccentricity effects on arrow discrimination. The substrates of the attentional networks were also affected by eccentricity; the far eccentricity showed smaller orienting effect scores and larger executive control scores than the near eccentricity. Furthermore, we also found that the eccentricity effect on executive control was modulated by cue type. The allocation of attentional resources differed between the cue conditions and influenced the interference caused by conflicting information.

Author Note

Bin Wang and Jingjing Zhao are co-first authors.

Declaration of Conflicting Interests

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