Testing the Efficiency and Independence of Attentional Networks

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Abstract

■ In recent years, three attentional networks have been defined in anatomical and functional terms. These functions involve alerting, orienting, and executive attention. Reaction time measures can be used to quantify the processing efficiency within each of these three networks. The Attention Network Test (ANT) is designed to evaluate alerting, orienting, and executive attention within a single 30-min testing session that can be easily performed by children, patients, and monkeys. A study with 40 normal adult subjects indicates that the ANT produces reliable single subject estimates of alerting, orienting, and executive function, and further suggests that the efficiencies of these three networks are uncorrelated. There are, however, some interactions in which alerting and orienting can modulate the degree of interference from flankers. This procedure may prove to be convenient and useful in evaluating attentional abnormalities associated with cases of brain injury, stroke, schizophrenia, and attention-deficit disorder. The ANT may also serve as an activation task for neuroimaging studies and as a phenotype for the study of the influence of genes on attentional networks. ■

INTRODUCTION

The neural basis of attention has been viewed in terms of large-scale neural networks corresponding to areas active during imaging tasks that require attention and regions, which, when damaged, produce attentional deficits (Posner & Petersen, 1990; Mesulam, 1981). Posner and Petersen (1990) have argued that consideration of the function of these various brain areas can be usefully separated into areas associated with the sources of attention and areas in which attention has its influence on specific forms of information processing (sites). For example, under some circumstances, attention can influence the primary visual cortex, but the source of this effect may lie elsewhere (Martinez et al., 1999; Posner & Gilbert, 1999). Although there has been some evidence that attentional effects may be a result of conflict within many separated brain areas (Desimone & Duncan, 1995), recent studies have shown clear evidence for a top-down network activated even before the presentation of the to-be-attended stimuli (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999).

Posner and Petersen (1990) proposed that the sources of attention form a specific system of anatomical areas, which can be further broken down into three networks. These networks carry out the functions of alerting, orienting, and executive control. Alerting is defined as achieving and maintaining an alert state; orienting is the selection of information from sensory input; and executive control is defined as resolving conflict among responses.

The alerting system has been associated with the frontal and parietal regions of the right hemisphere because continuous performance and vigilance tasks activate different levels of alertness, and such tasks activate the frontal and parietal regions of the right hemisphere. This is thought to be due to the cortical distribution of the brain's norepinephrine system (NE) (Coull, Frith, Frackowiak, & Grasby, 1996; Marrocco, Witte, & Davidson, 1994).

The orienting system has been associated with areas of the parietal and frontal lobes. Orienting is manipulated by presenting a cue indicating where in space a person should attend, thereby providing a basis for the person to direct attention to the cued location either overtly by moving the eyes or covertly without any eye movement (Posner, 1980). Event-related functional magnetic resonance imaging (fMRI) studies have suggested that the superior parietal lobe is associated with orienting following the presentation of a cue (Corbetta et al., 2000). The superior parietal lobe in humans is closely related to the lateral intraparietal area (LIP) in monkeys, which is known to produce eye movements (Anderson, Snyder, Bradley, & Xing, 1997). When a target occurs at an uncued location, and attention has to be disengaged and moved to a new location, there is activity in the temporal-parietal junction (Corbetta et al., 2000).

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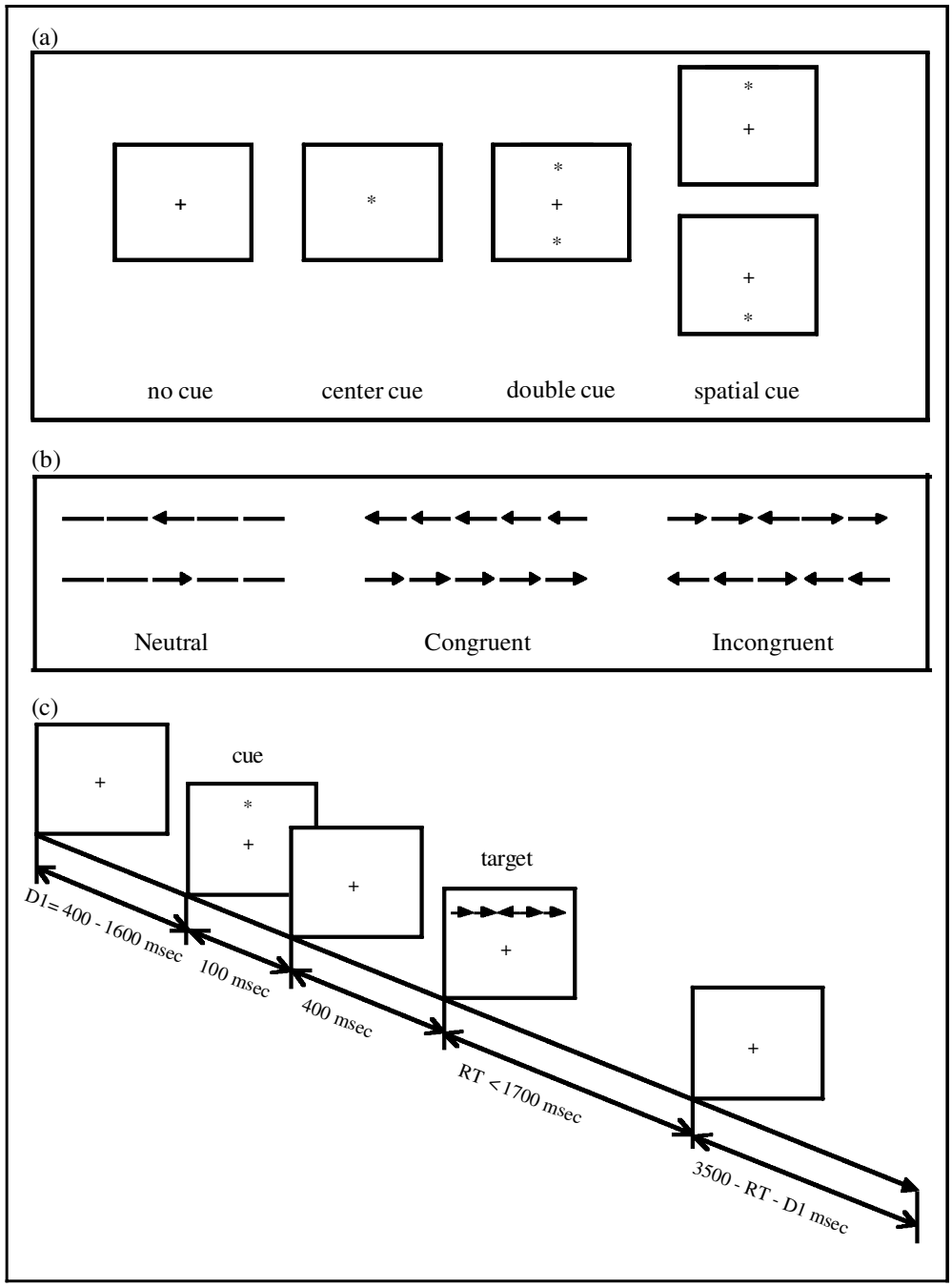


Figure 1. Experimental procedure. (a) The four cue conditions; (b) The six stimuli used in the present experiment; and (c) An example of the procedure.

Lesions of the temporal- parietal junction are most likely to produce a difficulty in disengaging to deal with stimuli in a direction opposite the lesion (Friedrich, Egly, Rafal, & Beck, 1998).

Executive control of attention is often studied by tasks that involve conflict, such as various versions of the Stroop task, which activate midline frontal areas (anterior cingulate) and the lateral prefrontal cortex (Bush, Luu, & Posner, 2000; MacDonald, Cohen, Stenger, & Carter, 2000). There is now considerable evidence for their common activation in tasks involving conflict and other forms of mental effort (Bush et al., 2000). Recently, other tasks involving cognitive conflict, such as variations of the flanker task developed by Eriksen and Ericksen (1974), have been shown to activate several areas involved in the executive attention network, but in functionally distinct ways. These experimental tasks may provide a means of fractionating the functional contributions of areas within the executive attention network (Casey et al., 2000; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999).

We have confirmed that the flanker task activates an area of the anterior cingulate, which is distinct from, but overlaps, activations produced by other conflict tasks (Fan, McCandliss, Flombaum, Thomas, & Posner, 2001).

Table 1. Means RT and Error Rates Under Each Condition

	Warning Type			
Congruency	*None*	*Center*	*Double*	*Up/Down*
(a) Mean RTs (msec) and standard deviations:				
Congruent	530 (49)	490 (48)	479 (45)	446 (41)
Incongruent	605 (59)	585 (57)	574 (57)	515 (58)
Neutral	529 (47)	483 (46)	472 (44)	442 (39)
(b) Error rate (%) and standard deviations:				
Congruent	0.73 (0.21)	0.54 (0.19)	0.59 (0.19)	0.44 (0.18)
Incongruent	3.49 (0.67)	4.88 (0.68)	4.27 (0.70)	3.51 (0.47)
Neutral	1.17 (0.33)	0.93 (0.22)	1.56 (0.29)	0.78 (0.23)

We have also programmed a version of the full Attention Network Test (ANT) for fMRI studies. The goal of the present research is to build upon this work to develop a behavioral task which (1) clearly involves all three attentional networks, (2) could be used to obtain a measure of the efficiency of each of the networks, and (3) is simple enough to obtain data from children, patients, and animals.

The development of such a measure would make it possible to determine if the three networks are functionally independent or if the activity of one network interacts or is correlated with the other networks. The same task could also be used with event-related functional imaging, to study the brain areas involved in each aspect of the task. The task could then be used to indicate which of the networks might be functioning abnormally in attentional disorders in clinical patients. The test could also be used to measure the influence of behavioral (Sohlberg, McLaughlin, Pavese, Heidrich, & Posner, 2000) and pharmacological (Swanson et al., 2000) interventions on each of the networks. Finally, the test could also serve as a phenotype for genetic studies designed to determine the sources of individual variation in network efficiency (Fan, Wu, Fossella & Posner, 2001; Fossella, Posner, Fan, Swanson & Pfaff, in press).

The ANT, illustrated in Figure 1, is a combination of the cued reaction time (RT) (Posner, 1980) and the flanker task (Eriksen & Eriksen, 1974). The ANT requires participants to determine whether a central arrow points left or right. The arrow appears above or below fixation and may or may not be accompanied by flankers. Efficiency of the three attentional networks is assessed by measuring how response times are influenced by alerting cues, spatial cues, and flankers. The task has been deliberately kept short and simple so that it can be used with adults, children, monkeys, and patients with various abnormalities of attention, and so that reliable estimates of the three networks can be obtained within a half hour.

Figure 1a shows the four cue conditions. Figure 1b shows the six target stimuli. Figure 1c illustrates the time course of a trial using a spatial cue with incongruent flankers.

RESULTS

Table 1a and Figure 2a summarize RT data pooled from correct trials in Sessions 1 and 2 as a function of cue and flanker condition. Error rates are shown in Table 1b and Figure 2b. A preliminary analysis showed no difference between left-pointing and right-pointing targets in any condition, so they were combined. A set of cognitive subtractions (described below) was used to assess the efficiency of the three attentional networks.

The alerting effect was calculated by subtracting the mean RT of the double-cue conditions from the mean RT of the no-cue conditions. Neither of these conditions provided information about whether the target stimulus would appear above or below the fixation point. When no warning cue is presented, attention tends to remain diffused across the two potential target locations. The double cue was used because it also tends to keep attention diffused between the two potential target locations, while alerting the participant to the imminent appearance of the target. The mean alerting effect was 47 msec with a standard deviation of 18 msec.

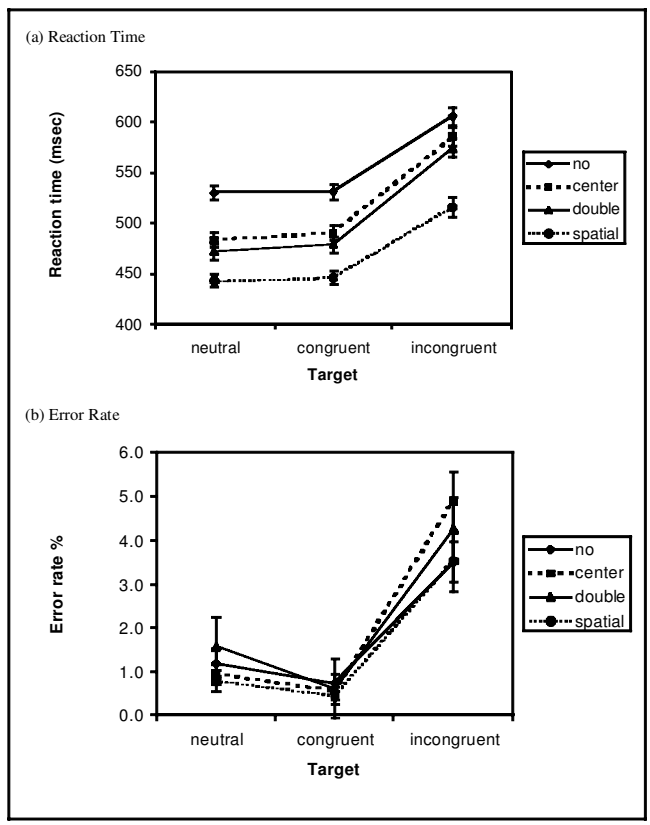


Figure 2. Results. (a) Mean RT from correct trials as a function of cue and flanker condition. (b) Error rate.

Table 2. Correlations between Attentional Networks and between Two Test Sessions

	Session 1				*Session 2*			*Combined*		
	Alerting	*Orienting*	*Conflict*	*Mean*[a]	*Alerting*	*Orienting*	*Conflict*	*Alerting*	*Orienting*	*Conflict*
Session 1										
Orienting	.10									
Conflict	−.14	−.16								
Mean	−.01	.25	.46**							
Session 2										
Alerting	.52**	−.07	.07	.01						
Orienting	.15	.61**	−.04	.26	.07					
Conflict	.06	−.20	.77**	.43**	.20	−.02				
Mean	.17	.22	.33*	.87**	.14	.28	.35*			
Combined										
Orienting								.08		
Conflict								.05	−.12	
Mean								.09	.29	.44**

[a]Mean of raw RT which is not the mean of the three effects.

*Correlation is significant at the .05 level (two-tailed).

**Correlation is significant at the .01 level (two-tailed).

The orienting effect was calculated by subtracting the mean RT of the spatial cue conditions from the mean RT of the center cue. Both center and spatial cues serve as a form of alerting cue, but only the spatial cue provides predictive spatial information that allows subjects to begin orienting attention to the appropriate location before the target arrives. The center cue was used as a control because, like the single cue, it encourages orienting attention to one location. The orienting effect had a mean of 51 msec with a standard deviation of 21 msec.

The conflict (executive control) effect was calculated by subtracting the mean RT of all congruent flanking conditions, summed across cue types, from the mean RT of incongruent flanking conditions. The use of neutral, instead of congruent, flanking conditions would produce the same result because there were only small differences between the congruent flanker and the neutral flanker conditions. The mean conflict effect was 84 msec with a standard deviation of 25 msec.

Correlation Analyses

Two goals of the correlation analyses were (a) to determine whether each 30-min test session provided a reliable estimate of the efficiency of the three networks for individual subjects, and (b) to assess whether or not subjects' efficiency within each of the networks was correlated. Table 2 shows the correlations among measures of the three attentional networks and includes a correlation between each attention measures and overall mean RT. Correlations are shown separately for each session and combined across the two sections. Correlations between the two sessions for a particular component provide an estimate of reliability for individual subjects. Estimates for each of the three networks and for the overall RT produced significant test- retest reliability. The correlations between the three components provided one way of looking at the independence of the networks. None of those were significant, although the mean RT did have a modest correlation with the conflict scores measuring executive control (.44).

Analysis of Variance (ANOVA)

We carried out a 4 (cue condition: no cue, center cue, double cue, spatial cue) × 3 (flanker type: neutral, congruent, incongruent) ANOVA of the RT data found in Table 1 and Figure 2a. There were significant main effects of cue condition [$F(3,117) = 291.99$, $p < .001$], and of flanker type [$F(2,78) = 438.86$, $p < .001$]. Additionally, there was a significant interaction between cue condition and flanker type [$F(6,234) = 17.43$, $p < .001$]. The nature of the interaction is readily apparent in Figure 2a. Under all cueing conditions, the presence of incon-

gruent flankers increased RT, however, this effect was enhanced when subjects were given alerting cues (center or double cues) that contained no spatial information.

A 4 × 3 ANOVA on accuracy scores, summarized in Table 1b, revealed only a main effect of flanker type [$F(2,78) = 42.62$, $MSE = .00$, $p < .001$]. Planned contrasts demonstrated a significant difference between incongruent flankers versus the combined conditions of congruent and neutral flankers [$F(1,39) = 46.90$, $MSE = .00$, $p < .001$]. Additionally, the difference between congruent and neutral condition was also significant [$F(1,39) = 7.49$, $MSE = .00$, $p < .01$]. In general, the accuracy data were consistent with the RT data in showing that incongruent flanking interfered with the processing of the target.

DISCUSSION

Task Design

We have succeeded in obtaining a measure of the operation of each of the three attentional networks within a single task requiring about a half hour to administer. Our previous effort to assay these effects prior to and after the attention process therapy for patients with closed-head injury required about 3 hr (Sohlberg et al., 2000). Moreover, our new task is extremely simple, allowing us to develop an age-appropriate version for children as young as 4 years of age. The instructions to the subjects only require that they know how to press a left key for a leftward-pointing arrow and a right key for a rightward-pointing arrow. There is substantial evidence that the alerting and orienting cues would operate even without any voluntary instruction (Lambert, Naikar, McLachlaen, & Aitken, 1999).

Reliability

The cognitive subtractions provide three numbers that together describe the efficiency of each of the three attentional networks. Whereas the raw RT are highly correlated across the two sessions (.87), the subtractions are somewhat less reliable. The alerting network appears to be the least reliable with a test-retest correlation of (.52), whereas the executive control network is the most reliable (.77) and the orienting network is intermediate (.61).

Independence

We began with the observation that three sources of attention, alerting, orienting, and executive attention, appear to engage separate brain mechanisms. One way we used to assess the functional independence of these three networks was to examine how correlated these three efficiency estimates were across the 40 subjects tested. Results demonstrate no correlation between any combination of alerting, orienting, and conflict resolution, suggesting that these are functionally orthogonal constructs.

Another measure of independence involves the ANOVA approach, examining whether there are significant interactions between the experimental factors that influence the alerting network (presence or absence of cues without spatial information), the orienting network (presence or absence of cues with spatial information), and the executive control network (incongruent vs. congruent or neutral flankers). The ANOVA yielded significant effects of cue type and flanker type and a significant interaction between the two. When an alerting cue with no spatial information was presented beforehand, the amount of flanker interference was enhanced relative to the no-cue and spatial-cue conditions.

This statistical interaction between factors suggests that the networks do not generally operate independently in all situations. It is possible that the interactions can be accounted for in terms of specific characteristics of the task. Use of spatial cues, which permit participants to direct attention to the target stimulus ahead of time, could potentially reduce the influence of the surrounding flankers. The reduced flanker interference in the no-cue condition is more surprising. We expected both the no-cue and double-cue conditions to produce relatively diffuse attention and thus expected both to have the same flanker interference. The no-cue condition is a relatively low-alertness condition and resulted in longer RTs and lower error rates. This speed-accuracy tradeoff is usual for the effect of alertness on RT (Posner, 1978). In previous studies, it has been shown that information builds up at the same rate regardless of the level of alertness, but the criterion for response is more stringent when alertness is low. It is possible that the longer time to produce a response due to low alertness can provide additional time for executive attention processes in the conflict condition, and thus the differences between congruent and incongruent flanker conditions are reduced.

We have just completed a new study using the ANT with 7-year-old children. The child version uses a fish display that provides animated feedback for the children rather than the static arrows. While the children had much longer RT, our analysis of the subtractions suggests that orienting is very similar to the adult data while alerting and conflict differ. The child version gave no evidence for either of the interactions found in the adult data.

Further support for the independence of these networks under some circumstances comes from a study of orienting and the classical color Stroop effect (Shalev & Algom, 2000), in which the two effects were found not to interact. Overall, it appears that there are some interactions between the networks suggesting that they may not prove to be independent in all behavioral studies even though they use different anatomy and chemical modulators.

Eye Movements

One possible reason for the two interactions observed in the adult study is the relatively high-acuity demand of the arrow version of the task. We did not control for eye movements because the work of Corbetta and associates (e.g., Corbetta, 1998) has shown that overt and covert shifts of attention use the same anatomy. However, we did run a few subjects either under instruction to avoid eye movements, as in the full study described in this paper, as well as with no instruction to maintain fixation. Under instruction to maintain fixation, eye movements were relatively rare (about 3- 5% of all trials). When no instruction was given, eye movements were very common. RT appeared to be faster in eye-movement trials, however, the basic effects of cues and target looked very similar. The interactions found in the full study were probably not due to eye movements, but are very likely influenced a great deal by the acuity demands of the task.

Reliability and Practice

In this study, the executive network measure was far more reliable than the others. This is most likely due to the fact that alerting and orienting were introduced by cues while the executive functions were measured directly by the task. There is a degree of option in the use of the cues that might have reduced their reliability. When orienting as manipulated by validity functions, it might be more reliable, but of course, it would require many more trials. Auditory alerting cues often produce more automatic alerting than do visual cues and they might serve to aid reliability of the alerting manipulation. The method used to measure reliability confounded it with practice since the second session clearly involved more practice than the first. However, there is little evidence that there are major practice effects in this task since the difference scores did not change significantly between sessions, although the overall RTs of the second session was faster than that of the first session.

Future Studies

We are currently employing the ANT in a number of ongoing studies. One of them involves development of a version that engages children in a game using pointed goldfish as the target and flankers. Preliminary results with children support most of the findings in this study, although no interactions between cue and target were found.

Another goal is to use this task to assess the success of efforts to develop rehabilitation methods. Sturm, Willmes, Orgass, and Hartje (1997) argued that rehabilitative techniques need to be targeted to specific attentional networks and that some networks cannot be altered without first changing other networks (see also Sohlberg et al., 2000). The test should allow assessment of these ideas. An extension of this idea is to use the task to assay the effects of various forms of attentional instruction.

Studies with alert monkeys have related each of the networks with specific neurotransmitters. In the case of alerting, blocking the NE systems blocks the normal effect of warning signals (Marrocco, Witte, & Davidson, 1994). Injections of scopolamine into the LIP area have been shown to have a specific effect on orienting (Davidson & Marrocco, 2000), suggesting the relation of this network to acetylcholine (ACh). Finally the anterior cingulate and the lateral frontal cortex are target areas of the ventral tegmental dopamine system. We believe that individual differences in the networks may result from differences in genotypes (Swanson et al., 2000) related to these networks. The association between networks and particular chemical modulators suggests specific predictions as to which polymorphisms will be related to each attentional network.

We have written the behavioral assay using both of the E-Prime package and Java applet for possible execution on IBM-compatible personal computers. To expedite its use by anyone who desires to make further tests, we have placed the program at http://www.sacklerinstitute.org.

METHODS

Subjects

Forty paid, adult volunteers between the ages of 20 and 44 (mean age 30.1 years, 23 women and 17 men) participated in the experiment. All participants reported normal or corrected-to-normal vision. A signed informed consent approved by the New York Presbyterian Hospital/Weill Medical College of Cornell University was obtained from each participant prior to the experiment.

Apparatus and Stimuli

Stimuli were presented via E-Prime, a commercial experiment application, on an IBM-compatible personal computer running Windows 95, presenting to a 14-in. NEC SVGA monitor. Participants viewed the screen from a distance of 65 cm, and responses were collected via two input keys on a keyboard that rested on their lap.

Stimuli consisted of a row of five visually presented horizontal black lines, with arrowheads pointing leftward or rightward, against a gray background (see the three flanker conditions in Figure 1b). The target was a leftward or rightward arrowhead at the center. This target was flanked on either side by two arrows in the same direction (congruent condition), or in the opposite direction (incongruent condition), or by lines (neutral condition). The participants' task was to identify the direction of the centrally presented arrow by pressing one key for the left direction and a different key for the right direction. A single arrow or line consisted of 0.55° of visual angle and the contours of adjacent arrows or lines were separated by 0.06° of visual angle. The stimuli

(one central arrow plus four flankers) consisted of a total 3.08° of visual angle.

Each trial consisted of five events. First, there was a fixation period for a random variable duration (400-1600 msec). Then, a warning cue was presented for 100 msec. There was a short fixation period for 400 msec after the warning cue and then the target and flankers appeared simultaneously. The target and flankers were presented until the participant responded, but for no longer than 1700 msec. After participants made a response, the target and flankers disappeared immediately and there was a posttarget fixation period for a variable duration which was based on the duration of the first fixation and RT (3500 msec minus duration of the first fixation minus RT). After this interval the next trial began. Each trial lasted for 4000 msec. The fixation cross appeared at the center of the screen during the whole trial. To introduce an attentional-orienting component to the task, the row of five stimuli were presented in one of two locations outside the point at which the subject was fixating, either 1.06° above or below the fixation point. Target location was always uncertain except when spatial cue was presented.

To measure alerting and/or orienting, there were four warning conditions: no cue, center cue, double cue, and spatial cue. For the no-cue trials, participants saw only a fixation for 100 msec. Under this condition, there were neither alerting nor spatial cues. For the center-cue trials, participants were shown an asterisk at the location of fixation cross for 100 msec. Therefore, alerting was involved. For the double-cue trials, the time course was the same as in the center-cue trials except that there were two warning cues corresponding to the two possible target positions—up and down. It was expected that the alerting was involved but the attentional field was larger under the double-cue condition than under the central-cue condition. For the spatial-cue trials, the cue was at the target position and the time course was the same as in the center-cue and double-cue trials. The spatial cues were always valid, which means that they were displayed right on the locations of the targets. It was expected that both alerting and orienting were involved under this condition. The variable duration of the first fixation was used to produce additional uncertainty about cue onset.

Design

The experimental design was factorial, with two within-subject factors: cue type (no cue, center cue, double cue, or spatial cue) and flanker type (neutral, congruent, or incongruent).

Procedure

A session consisted of a 24-trial full-feedback practice block and three experimental blocks of trials with no feedback. Each experimental block consisted of 96 trials (4 cue conditions × 2 target locations × 2 target directions × 3 flanker conditions × 2 repetitions). The presentation of trials was in a random order. Participants were instructed to focus on a centrally located fixation cross throughout the task, and to respond as quickly and accurately as possible. During the practice trials, but not during the experimental trials, subjects received feedback from the computer on their speed and accuracy. The practice block took approximately 2 min and each experimental block took approximately 5 min. Each of the subjects ran in two sessions during 1 day. Between the two sessions, participants performed a color Stroop task for 10 min. Overall, this took about 1 hr. The results of the Stroop task and the correlations among Stroop effect and attentional networks will be reported in another article.

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REFERENCES

Anderson, R. A., Snyder, L. H., Bradley, D. C., & Xing, J. (1997). Multimodal representation of space in the posterior parietal cortex in planning movements. *Annual Review of Neuroscience, 20,* 303-330.

Botvinick, M., Nystrom, L. E., Fissell, K., Carter, C. S., & Cohen, J. D. (1999). Conflict monitoring versus selction-for-action in anterior cingulate cortex. *Nature, 402,* 179-181.

Bush, G., Luu, P., & Posner, M. I. (2000). Cognitive and emotional influences in the anterior cingulate cortex. *Trends in Cognitive Science, 4,* 215-222.

Casey, B. J., Thomas, K. M., Welsh, T. F., Badgaiyan, R., Eccard, C. H., Jennings, J. R., & Crone, E. A. (2000). Dissociation of response conflict, attentional selection, and expectancy with functional magnetic resonance imaging (fMRI). *Proceedings of the National Academy of Sciences, U.S.A., 97,* 8728-8733.

Corbetta, M. (1998). Frontoparietal cortical networks for directing attention and the eye to visual location: Identical, independent, or overlapping neural systems? *Proceedings of the National Academy of Sciences, U.S.A., 95,* 831-838.

Corbetta, M, Kincade, J. M., Ollinger, J. M., McAvoy, M. P., & Shulman, G. (2000). Voluntary orienting is dissociated from target detection in human posterior parietal cortex, *Nature Neuroscience, 3,* 292-297.

Coull, J. T., Frith, C. D., Frackowiak, R. S. J., & Grasby, P. M. (1996). A fronto-parietal network for rapid visual information processing: A PET study of sustained attention and working memory. *Neuropsychologia, 34,* 1085-1095.

Davidson, M. C., & Marrocco, R. T. (2000). Local infusion of scopoplamine into intraparietal cortex slows cover orienting

in rhesus monkeys. *Journal of Neurophysiology, 83,* 1536-1549.
Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annals of Neurology, 18,* 193-222.
Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception and Psychophysics, 16,* 143-149.
Fan, J., McCandliss, B. D., Flombaum, J. I., Thomas, K. M., & Posner, M. I. (2001, March). *Comparing images of conflict in frontal cortex.* Annual meeting of the Cognitive Neuroscience Society, New York, NY.
Fan, J., Wu, Y., Fossella, J., & Posner, M. I. (2001). Assessing the heritability of attentional networks. *BioMed Central Neuroscience, 2,* 14.
Fossella, J., Posner, M. I., Fan, J., Swanson, J. M., & Pfaff, D. M. (in press). Attentional phenotypes and higher mental function. *The Scientific World, 2.*
Friedrich, F. J., Egly, R., Rafal, R. D., & Beck, D. (1998). Spatial attention deficits in humans: A comparison of superior parietal and tempero-parietal junction lesions. *Neuropsychology, 12,* 193-207.
Kastner, S., Pinsk, M. A., De Weerd, P., Desimone, R., & Ungerleider, L. G. (1999). Increased activity in human visual cortex during directed attention in the absence of visual stimulation. *Neuron, 22,* 751-761.
Lambert, A. Naikar, N., McLachlaen, A., & Aitken, V. (1999). New component of visual orienting: Implicit effects of peripheral information and sub-threshold cues on covert attention. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 321-340.
MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science, 288,* 1835-1838.
Marrocco, R. T., Witte, E. A., & Davidson, M. C. (1994). Arousal systems. *Current Opinion in Neurobiology, 4,* 166-170.
Martinez, A., Anllo-Vento, L., Sereno, M. I., Frank, L. R., Buxton, R. B., Dubowitz, D. J., Wong, E. C., Hinrichs, H., Heinze, H. J., & Hillyard, S. A. (1999). Involvement of striate and extrastriate cortical areas in attention. *Nature Neuroscience, 2,* 364-369.
Mesulam, M.-M. (1981). A cortical network for directed attention and unilateral neglect. *Annals of Neurology, 10,* 309-325.
Posner, M. I. (1978). *Chronometric explorations of mind.* Hillsdale, NJ: Lawrence Erlbaum reissue 1986.
Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 41A,* 19-45.
Posner, M. I., & Gilbert, C. D. (1999). Attention and primary visual cortex. *Proceedings of the National Academy of Sciences, U.S.A., 96,* 2585-2587.
Posner, M. I., & Petersen, S. E. (1990). The attention systems of the human brain. *Annual Review of Neuroscience, 13,* 25-42.
Shalev, L., & Algom, D. (2000). Stroop and Garner effects in and out of Posner's beam: Reconciling two conceptions of selective attention. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 997-1017.
Sohlberg, M. M., McLaughlin, K. A., Pavese, A., Heidrich, A., & Posner, M. I. (2000). Evaluation of attention process therapy training in persons with acquired brain injury. *Journal of Clinical and Experimental Neuropsychology, 22,* 656-676.
Sturm, W., Willmes, K., Orgass, B., & Hartje, W. (1997). Do specific attention deficits need specific training? *Neuropsychological Rehabilitation, 7,* 81-103.
Swanson, J., Oosterlaan, J., Murias, M., Moyzis, R., Schuck, S., Mann, M., Feldman, P., Spence, M. A., Sergeant, J., Smith, M., Kennedy, J., & Posner, M. I. (2000). ADHD children with 7-repeat allele of the DRD4 gene have extreme behavior but normal performance on critical neuropsychological tests of attention. *Proceedings of the National Academy of Sciences, U.S.A., 97,* 4754-4759.